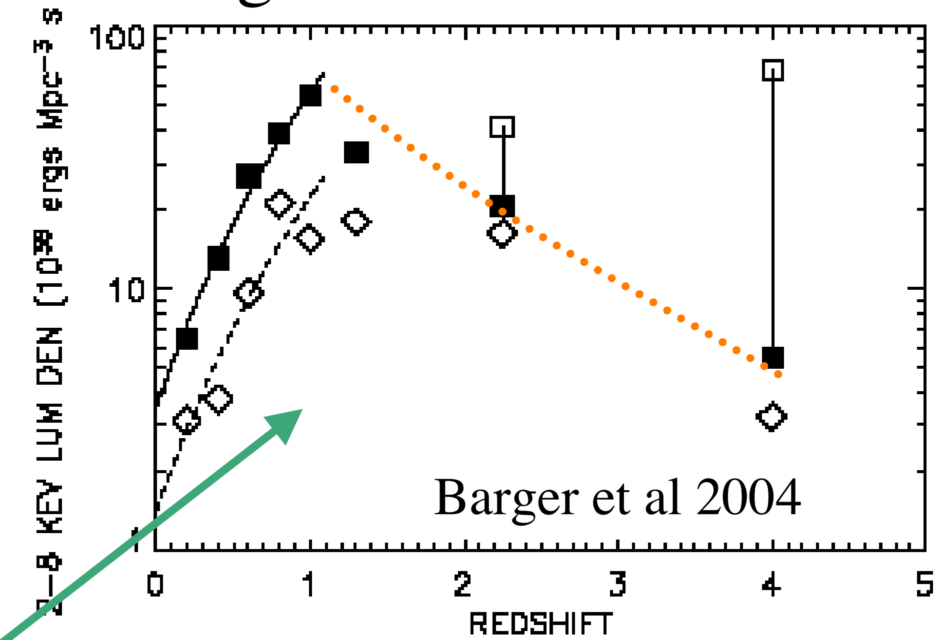
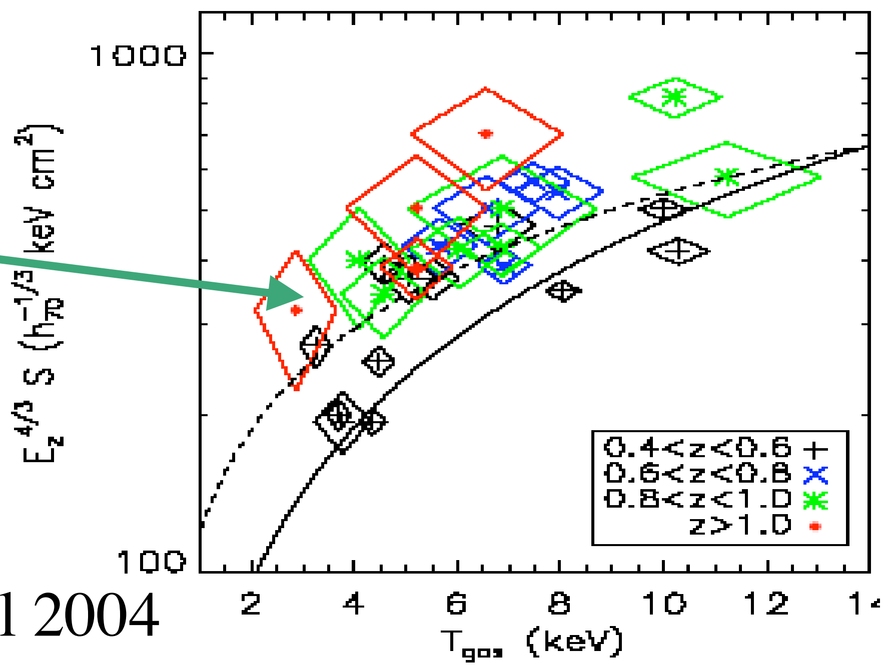
The One Thing

How the universe came to be the way it is

What has changed in the last 4 years

- We now know (Barger et al 2004, Heavens et al 2004, Conselice et al 2004, lots more) that
  - at z>1.5 the universe is very different from today
  - Most stars in the universe formed from 0.3<z<1.5
  - The epoch of black holes is z~1
  - Cluster evolution is doing something quite interesting at z~1
- CON-X is almost perfectly designed to study the z~1 universe (AGN, clusters and probably star formation)





Ettori et al 2004

Top New Cluster/Group Results in last 4 Years

- Physics of cooling flows*
- Existence of "cold" fronts
- Interaction of radio sources and x-ray plasma *
- Temperature and abundance profiles/structure
- Entropy of groups,clusters and galaxies *
- Dark matter structure of galaxies/clusters*
- Cluster evolution/cosmology *
- Existence of velocity structure
- Cluster merger dynamics

Somewhat more controversial

- "soft excesses" in clusters
- Existence of "hard" tails

Where does Con-X come in??

•Faster than XMM- more spectra per unit time, enable fainter objects, finer spatial resolution

•Better spectral resolution- plasma diagnostic, dynamics

•Hard x-ray imaging

Science drivers

• all structure forms from cooling flows- not understood-fundamental problem

•Structure formation models need "extra physics" is it AGN/radio sources

•Nature of dark matter hard to get at in other ways

•How the universe evolves

Rest of science is fascinating cluster physics

Clusters of Galaxies an X-ray Perspective

Probes of the history of structure formation

Dynamical timescales are not much shorter than the age of the universe

• Studies of their evolution, temperature and luminosity function can place strong constraints on all theories of large scale structure

• and determine precise values for many of the cosmological parameters

Provide a record of nucleosynthesis in the universe- as opposed to galaxies, clusters probably retain all the enriched material created in them

•Measurement of the elemental abundances and their evolution provide fundamental data for the origin of the elements

•The distribution of the elements in the clusters reveals how the metals were removed from stellar systems into the IGM

Clusters should be "fair" samples of the universe"

•Studies of their mass and their baryon fraction reveal the "gross" properties of the universe as a whole

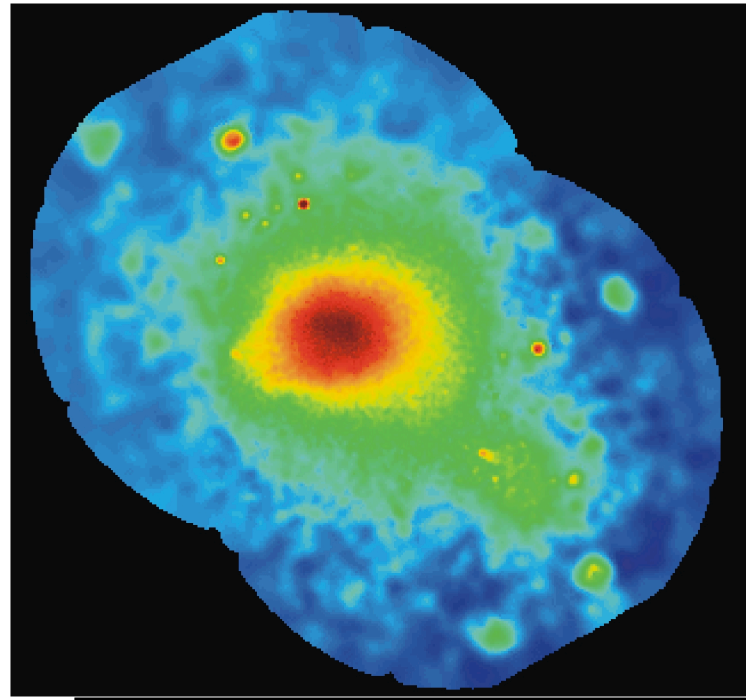
•Much of the entropy of the gas in low mass systems is produced by processes other than shocks-

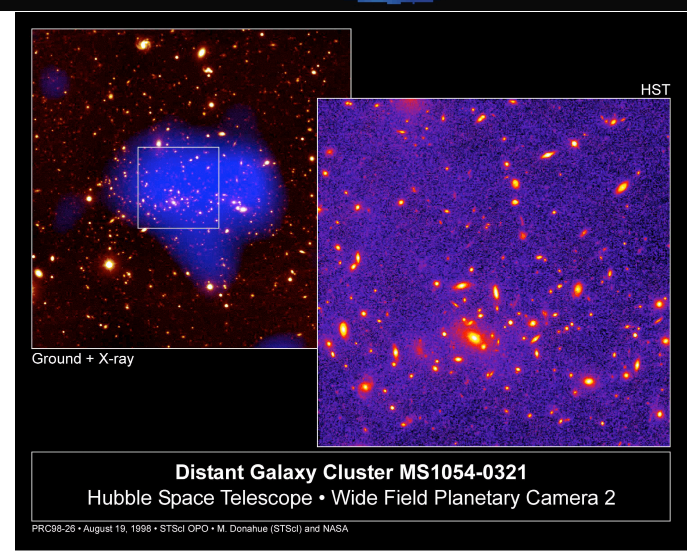
- a major source of energy in the universe ?
- a indication of the importance of non-gravitational processes in structure formation ?

Cluster Science Drivers

As extended sources with structure at all scales clusters are drivers for

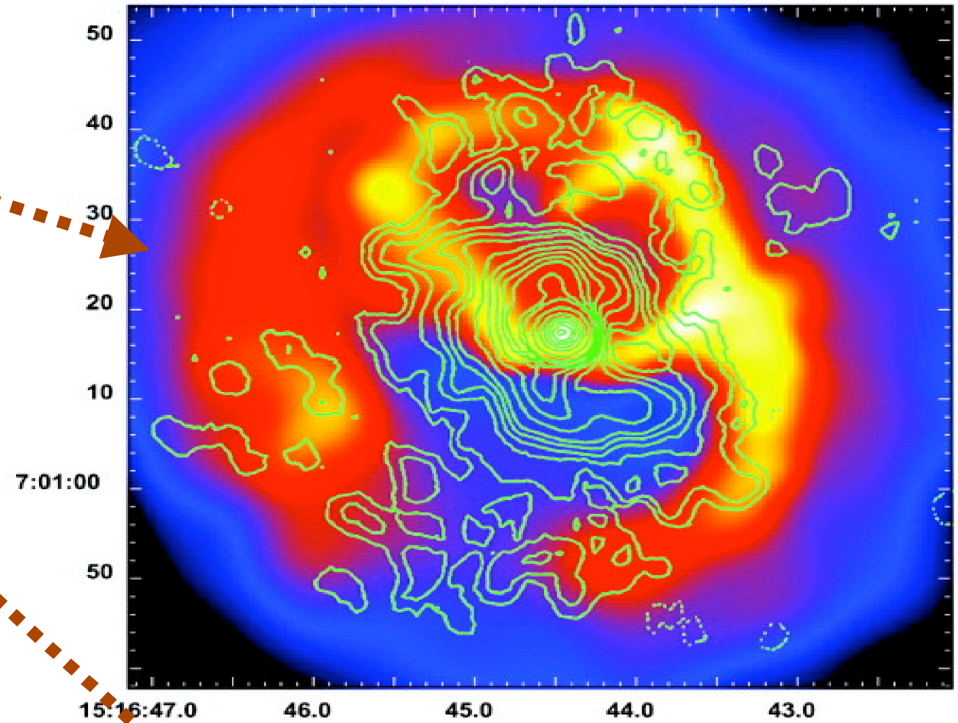
- Solid angle- a size of 2 Mpc at z~.1 is ~12'
- Angular resolution- radio source interaction/cooling flows structure to 1" in nearby systems
- Spectral resolution - plasma diagnostics and velocity structure to ~100 km/sec (in galaxies)
- Collecting area- surface brightness limited- if go to high angular resolution need large area
- Bandpass -
  - Ni abundances to derive typeII/type I ratio
  - N and C to compare to galaxies at high z
  - high energy for non-thermal phenomena
- Not a driver for timing

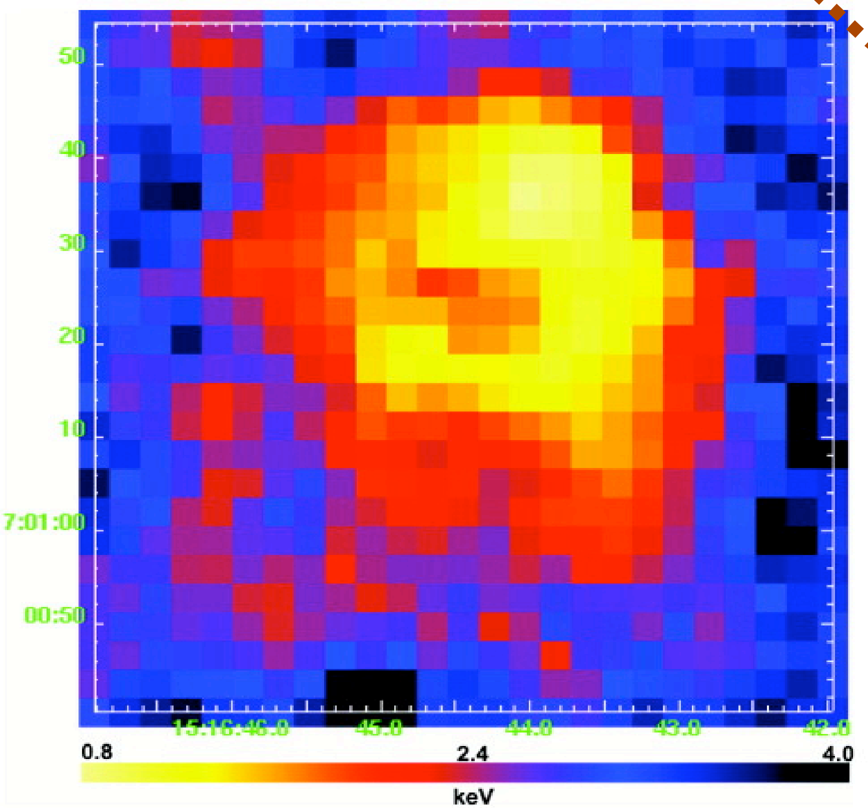


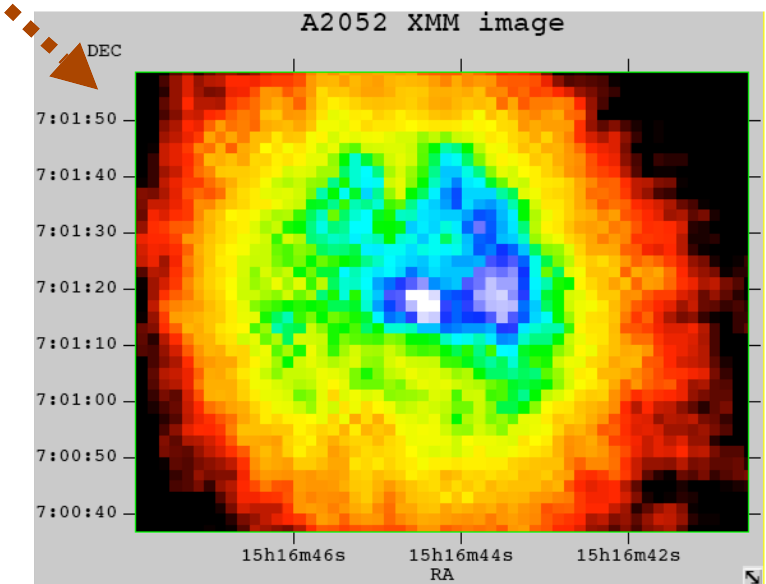


Chandra/XMM Images of Cooling Flows

- Chandra Image and temperature map of A2052 (z=0.0348)
- Structures are ~ 10” in size
- Compare XMM image - much of the structure is retained. - because FWHM is ~6” (lorentzian shape to beam)
- Conclude that at z<0.04 ~10” is adequate for imaging cooling flows need better resolution for higher z







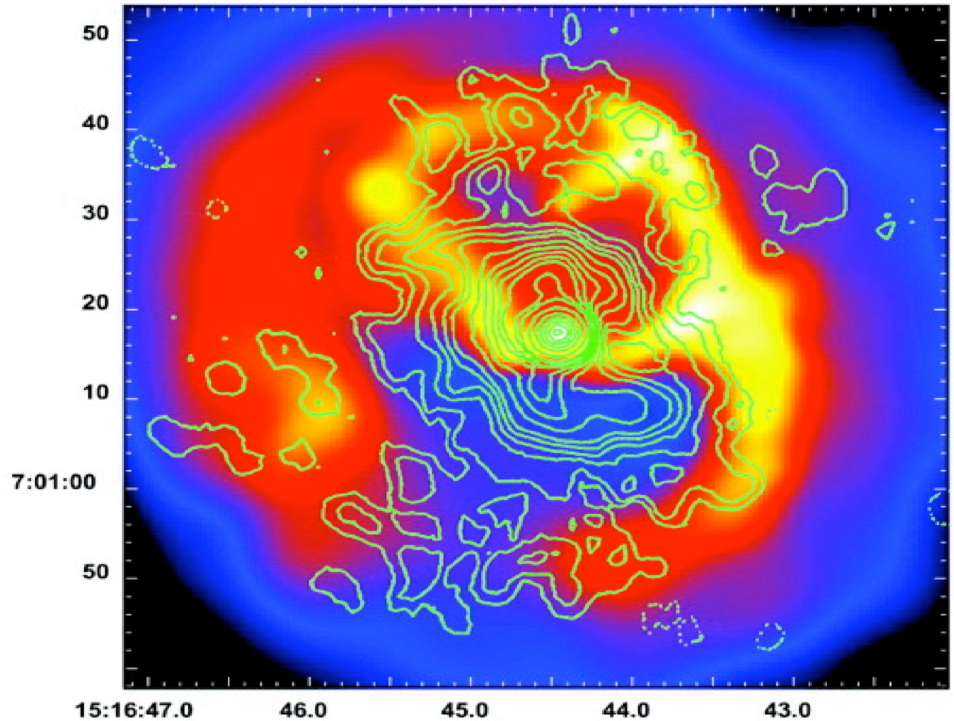
Cooling Flows

Why are cooling flows important?

- All structure in the universe is thought to form from the same basic idea-
  - dark matter coalesces under own gravity,
    - gas falls in,
    - shocks and gets heated to viral temperature,
    - cools and forms stars

This is exactly what a cooling flow is

- However the XMM and Chandra results show that we do not understand cooling flows
- Thus all calculations of the formation of structure is quite speculative.



Cooling Flows

- The question then becomes what sort of signal do we need with a 15” beam on cooling flow clusters.
- For A2052 in the bright ring to the west there are ~2x10-15 ergs/cm2/sec/arc-sec^2, 0.3-10 kev or ~6.3Con-X cts/15” beam (using xspec, PIMMS has 25 cts/beam)
- Using ~4000 cts for a good signal to noise a a 50ks exposure one could have a beam as small as 2” .
- Conclusion cooling flow clusters have such high surface brightness that small beams are supportable with reasonable exposures and the present Con-X collecting area (since surface brightness is conserved this holds to z~0.3) is acceptable.

Reflections of AGN Outbursts 9

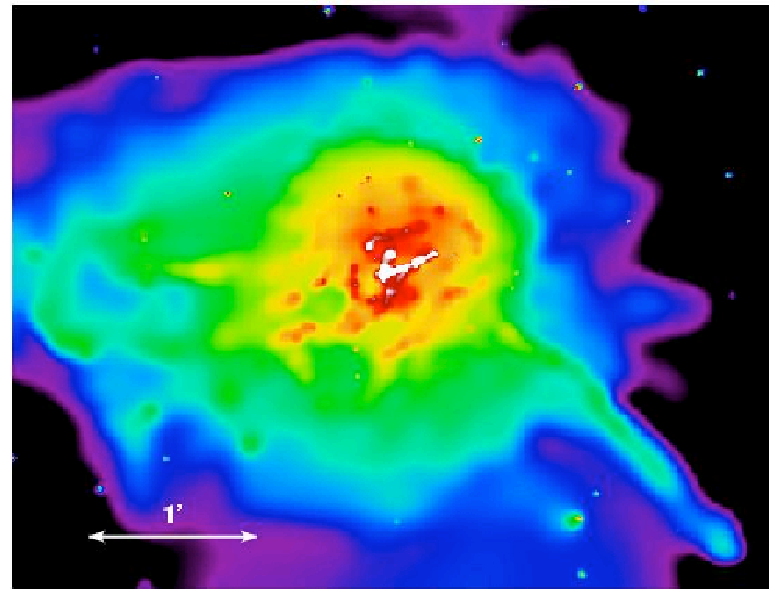
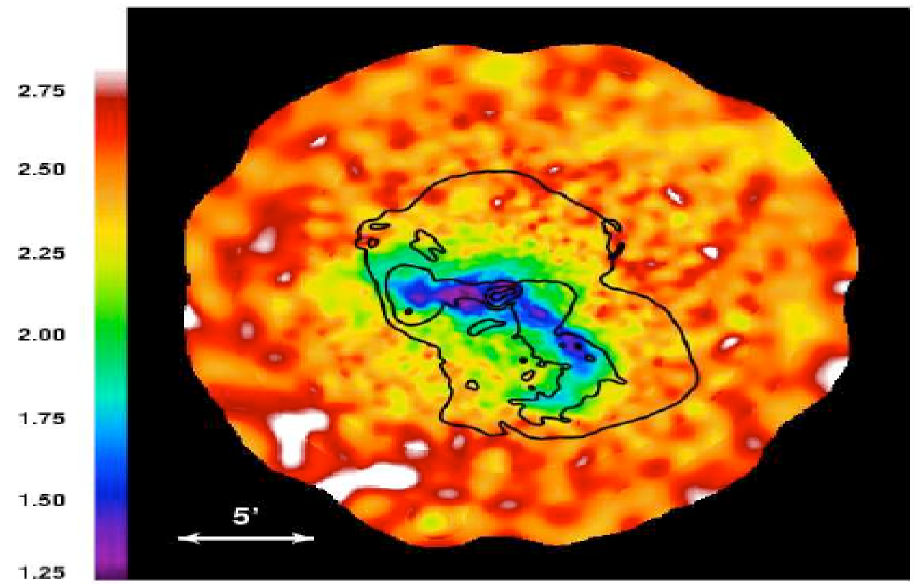
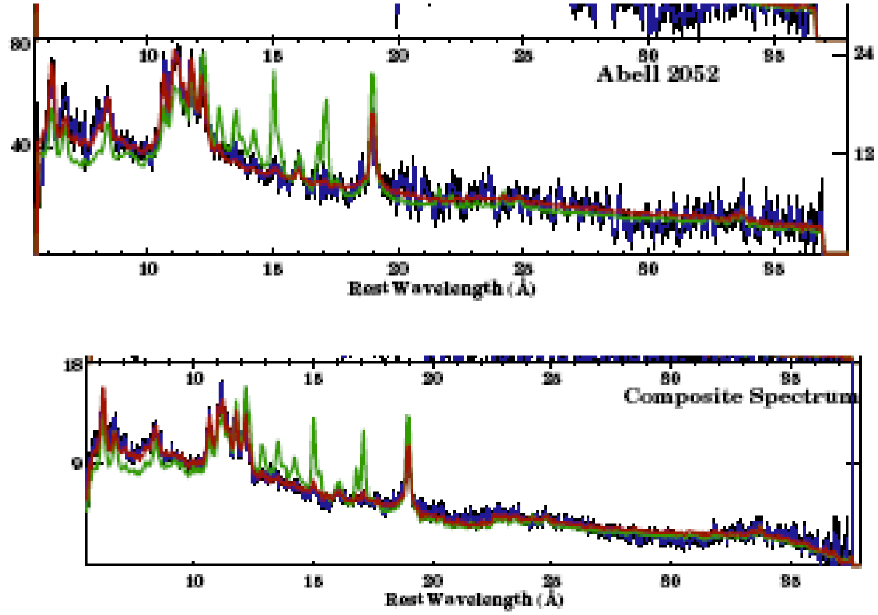


FIG. 2.— An adaptively smoothed Chandra image (minimum significance 4σ) of the central region of M87. Prominent features include the narrow southwestern arm, the bright 50″ radius inner core (yellow) which shows an especially sharp jump in surface brightness along the northern edge, and multiple bubbles and surrounding filaments in the core that form the base of the eastern arm.



Cooling Flows

- Problem with cooling flows in RGS data is the ‘absence’ of sufficient quantities of cool gas
- For A2052 and all other CF spectra there is a strong absence of gas at less than <T>/3
- Con-X will have
  - Much better resolution than the RGS for extended sources
  - Much higher signal to noise
  - True 2 D imaging
- 1-D spectra of M87 and a few other CFs



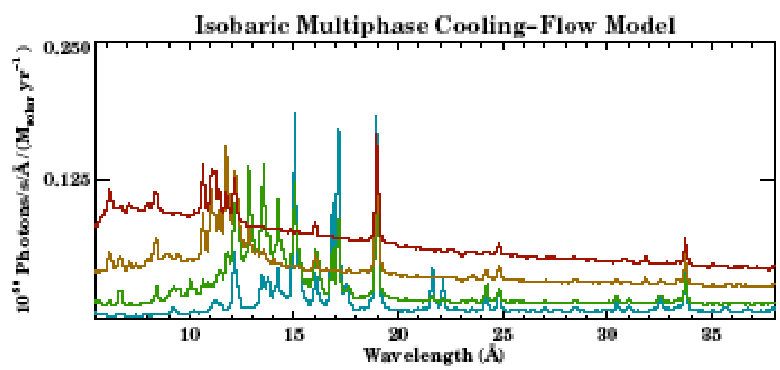


FIG. 3.— The emission spectrum of the standard cooling flow model broken up into several temperature bins. The red line shows the 3 to 6 keV spectrum, the yellow shows the 1.5 to 3 keV spectrum, the green shows the 0.75 to 1.5 keV spectrum and the blue shows the 0.375 to 0.75 keV spectrum. The normalization of each of the components is adjusted to see where the cooling flow model fails.

Interaction of radio sources and x-ray plasma

- Possible source of heat to "control" cooling flows, interaction of AGN with environment maybe very important in formation of structure in universe
- The radio emitting and x-ray emitting plasma's "know' about each other.
- There does not seem to be "obvious" heating of the gas by the relativistic particles
- Equipartition arguments do not seem to always work (e.g. in A2052 the gas pressure dominates by ~30 over magnetic fields)- not all clear what is going on- extra pressure could be from very hot gas ??
- No direct evidence for shock at radio/x-ray interface
- Not all systems show obvious structure in x-ray/radio images-

Where does Con-X come in??

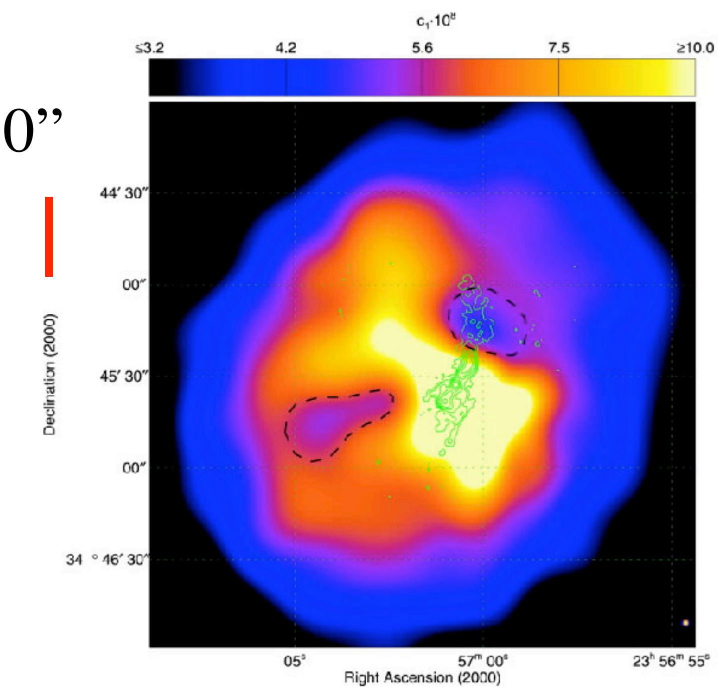
What is happening at the radio/thermal plasma interface- non-equilibrium effects, electron and ion temperatures.

Estimate of B fields from IC emission.

Problem with angular resolution?? - interaction regions small, radio sources small.

Cluster central radio sources tend to be small

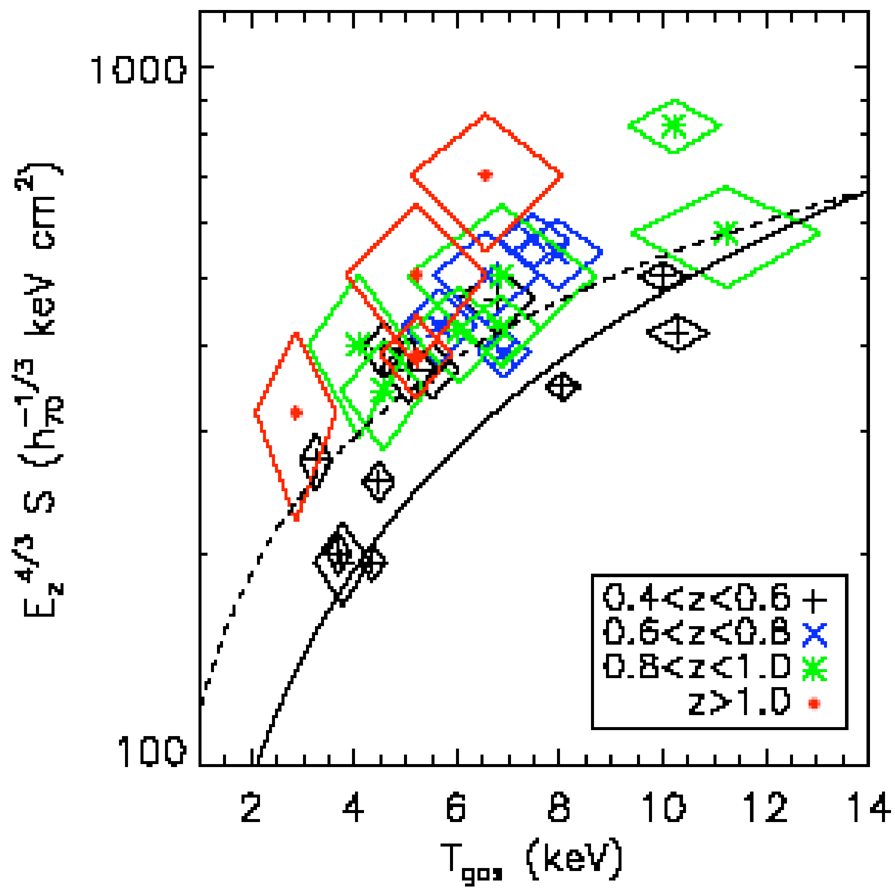
30"



A4059- x-ray image radio Contours

Cluster Evolution How the universe puts itself together!

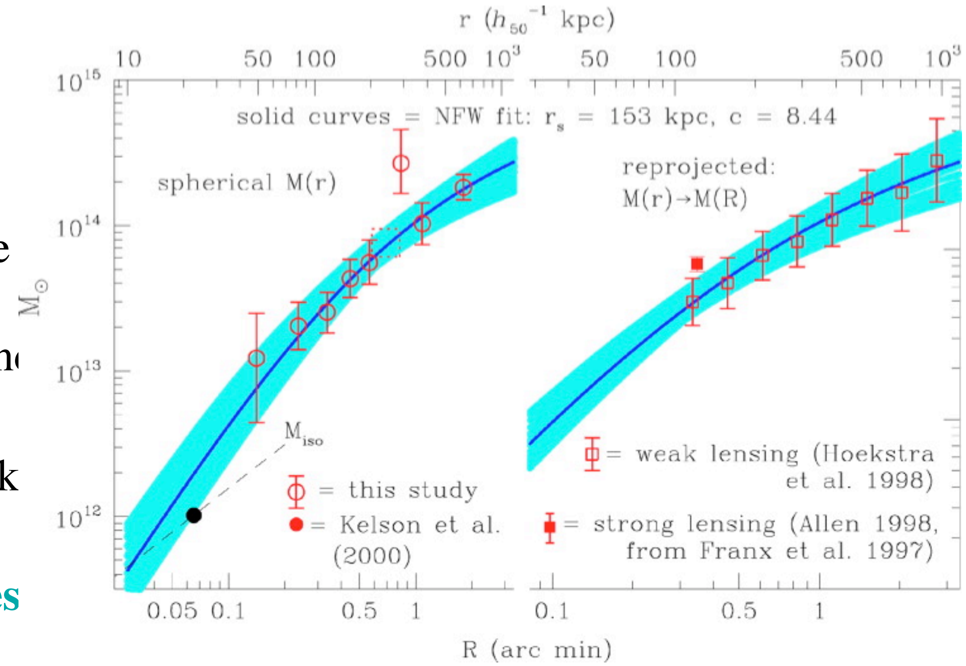
- Recent work (Ettori et al, Lumb et al Viklinin et al) indicate that clusters are not evolving with z as expected (no evolution in the M-T,T-L, abundance vs. z laws at z<0.6, but evidence for evolution at higher redshift)
- Perhaps the most intriguing results are
  - The absence of "cooling flows" a z>0,3
  - The evolution of cluster entropy
- Neither of these are understood
- Much higher quality spectra are required- at present the Chandra images seem to be "normal"



. Such results point toward a scenario in which a relatively lower gas density is present in high–redshift objects, thus implying a suppressed X–ray emission, a smaller amount of gas mass and a higher entropy level. This represents a non–trivial constraint for models aiming at explaining the thermal history of the intra–cluster medium out to the highest redshift reached so far.

Nature of dark Matter

- use gas to trace dark matter distribution on small scales near core- test nature of dark matter and form of potential
- Problem with Chandra is CCDs do not have sufficient spectral resolution to derive “unique” pressure distribution (Arzabajis an Bautz 2002)
- In two phase models if hot phase traces dark matter cool phase does not
- Con-X spectral resolution required- **also bes angular resolution one can afford**



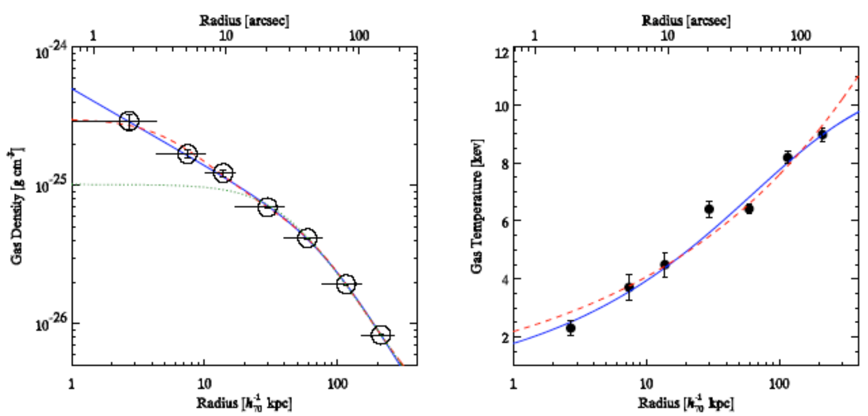


FIG. 1.— *Left Panel*: *Chandra* radial gas density profile of A2029. For clarity, large open circles are centered on the data points (the smallest error bars are difficul to see in the logarithmic scaling). Horizontal bars indicate the sizes of the annuli used to extract spectra, and the limits of the spherical shells in our de-projectec

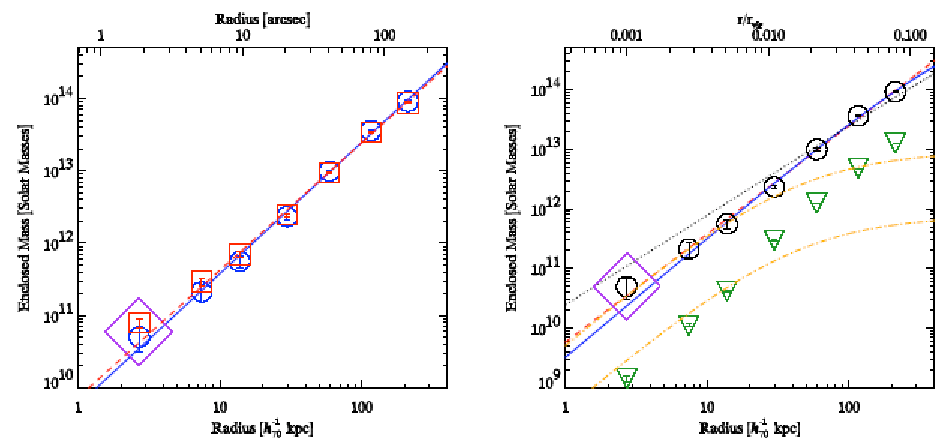
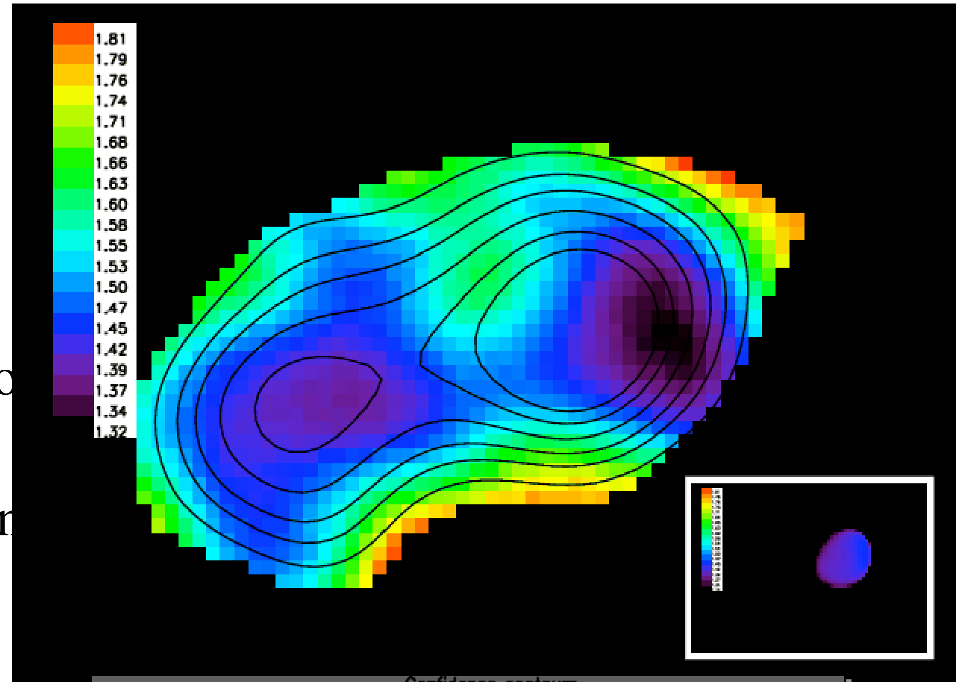
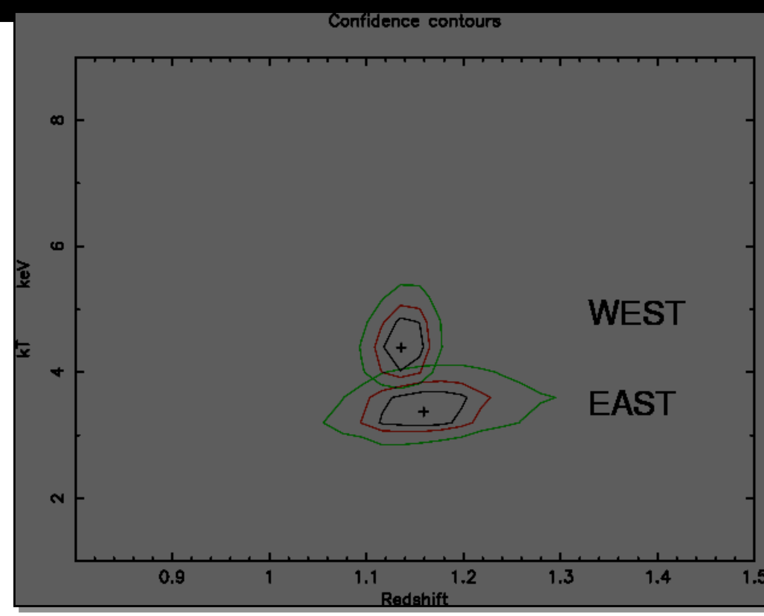


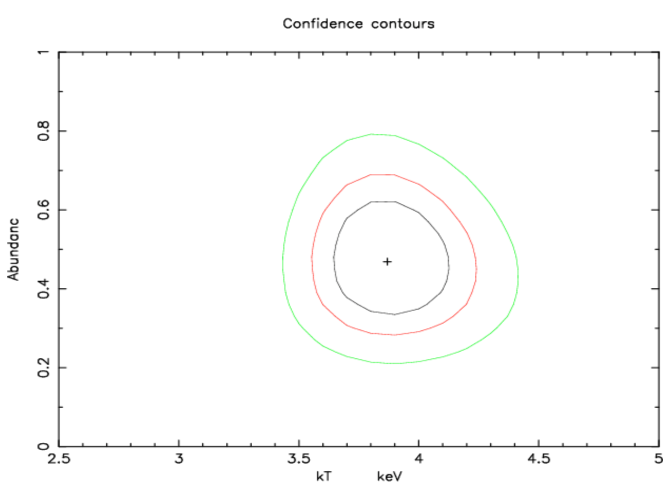
FIG. 2.— *Left Panel*: Total enclosed cluster mass, obtained from the B&M fit (*open circles*) and the power-law fit (*open squares*) to the temperature data. The

Cluster Evolution

- Con-X with much higher signal to noise and spectral resolution will provide precise temperatures and temperature profiles.
- Con-X can observe much lower luminosity systems and test models o their evolution.
- If it has a wide field instrument it car find clusters (~10/sq/deg at 10^{-14} ergs/cms^2/sec)
- As XMM has shown 15" is adequate for global cluster properties to z~1.3

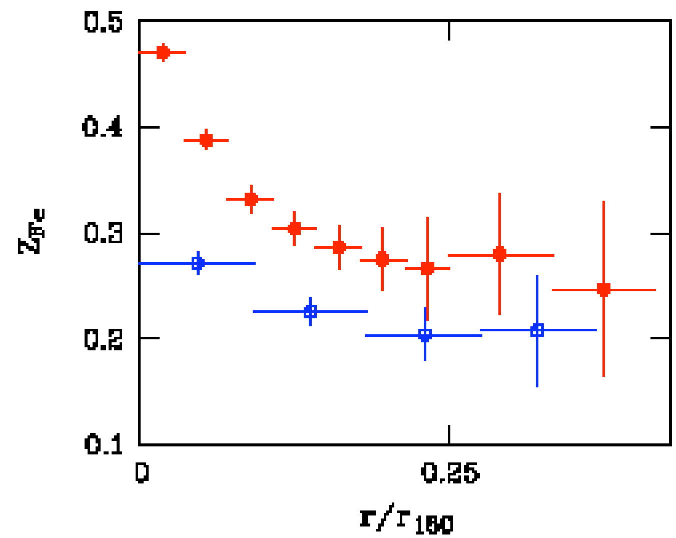




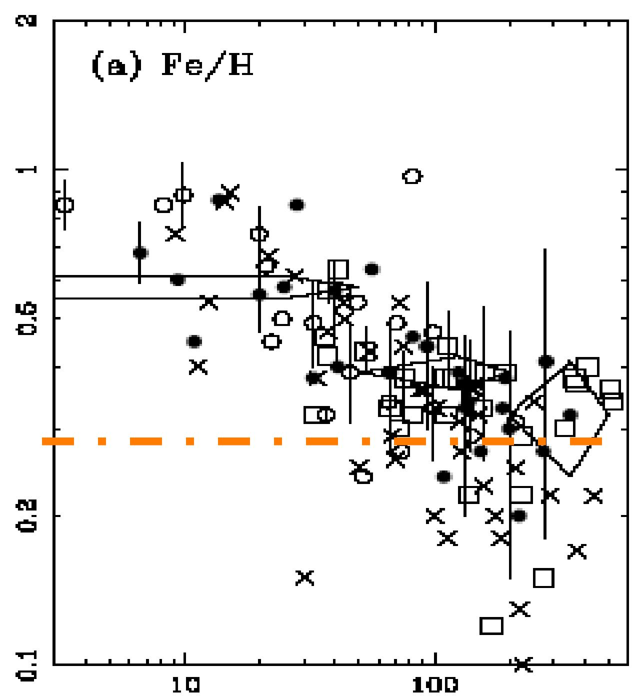


Abundance Profiles

- How, when and where the elements are created- clusters are the only fair samples in the universe, can obtain “good” data to z~1.4
- Study of cooling flows/abundance gradients at z>0.3 requires angular resolution of <15” (typical r_{cool} ~100kpc = 15” at z>0.7)
- Abundance gradients- using the Grandi and Molendi compilation strong abundance gradients also only occur inside ~0.1r_{virial} (~200kpc for a kT=8 keV cluster and smaller for lower temperature systems)
- There is often a sharp abundance Fe gradient in the central ~100kpc and only a weak gradient further out.
- The situation for Si and O is not so clear yet (more XMM data to come)



E 3. Mean Fe abundance profile from the BeppoSAX sample [25]. The sample
e (filled circles) and non cool core (empty circles) clusters. The radius is in units o
dance in solar units.



Temperature and abundance profiles/structure

- At larger physical scales, probe overall shape of dark matter, tota mass of cluster, total amount of metals
- Fundamental for comparison wit theory of structure growth

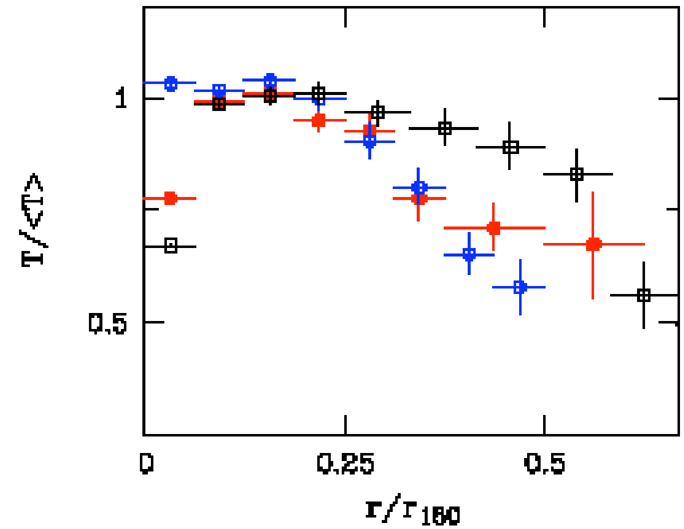


FIGURE 2. Mean temperature profile from BeppoSAX [16] (circles) and XMM-Newton [17] (squares) data. The BeppoSAX sample is divided in cool core (filled circles) and non cool core (empty circles) clusters. The radius is in units of r_{180} and the temperature in units of the cluster mean temperature.

- There is disagreement between XMM and ASCA/SAX on large scale temperature profiles c clusters - this is very important for determining the mass profile of clusters- Con-X **if it has a wide enough field of view**, will be the mission to answer this question

(SAX/ASCA have PSF problems, XMM and Chandra background subtraction problems)

Similar issues hold for abundance profiles/structure. There is, at present, little evidence for abundance structure (but see Iwasawa et al 2001,Saunders et al 2003)

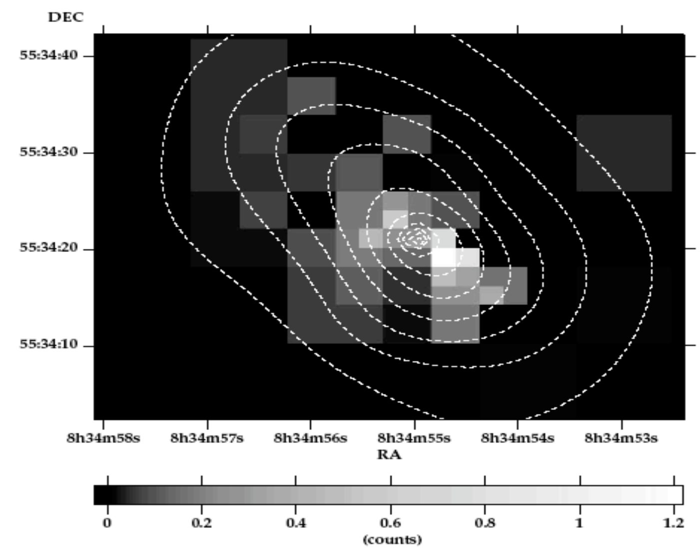
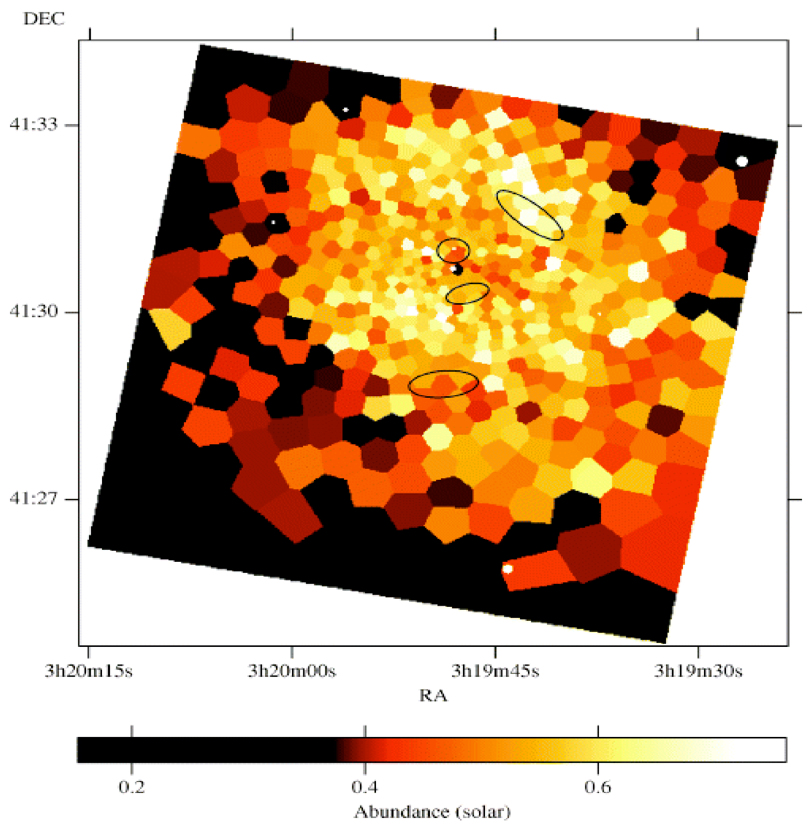
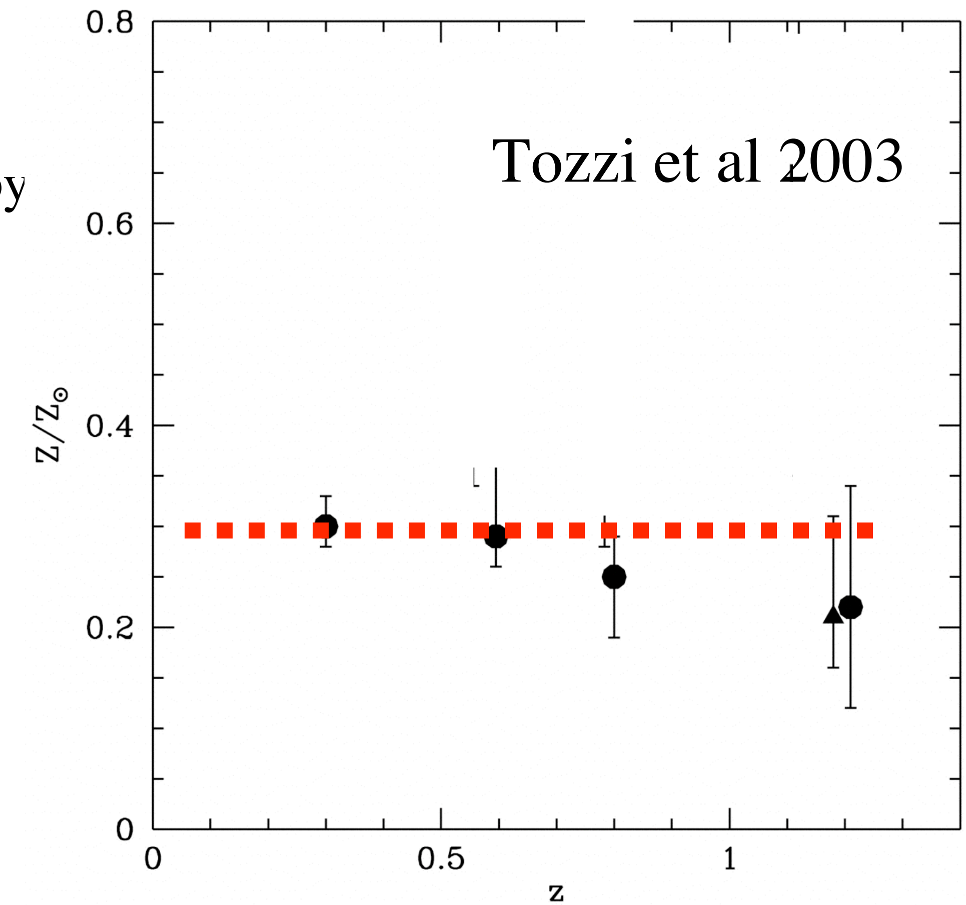


Figure 5. The continuum-subtracted Fe-L emission image of the central part of the cluster. The 0.78–1.0 keV (in the observed frame) image has

- To z~1.2 there is little evidence for evolution in the Fe abundance for massive clusters
- Con-X can go to z~1.7, if there are clusters to measure (perhaps found by Planck or other S-Z mission) .





Abundance map of Perseus cluster Saunders et al

Velocity Structure

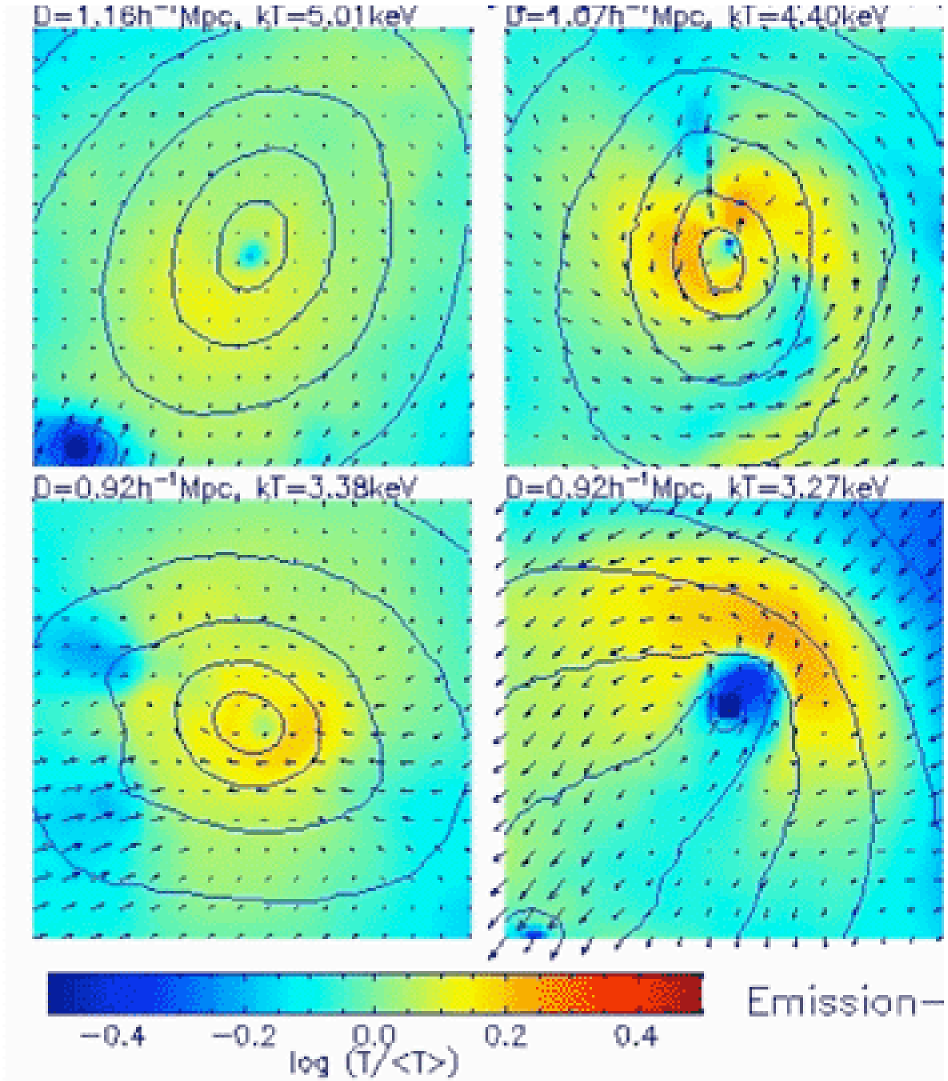
- All theories of cluster formation indicate that there should be lots of velocity structure

However not exactly clear how this constrains physics of cluster formation

- The optical depth of lines with high cross section has allowed the first indication of optical depth effects τ.

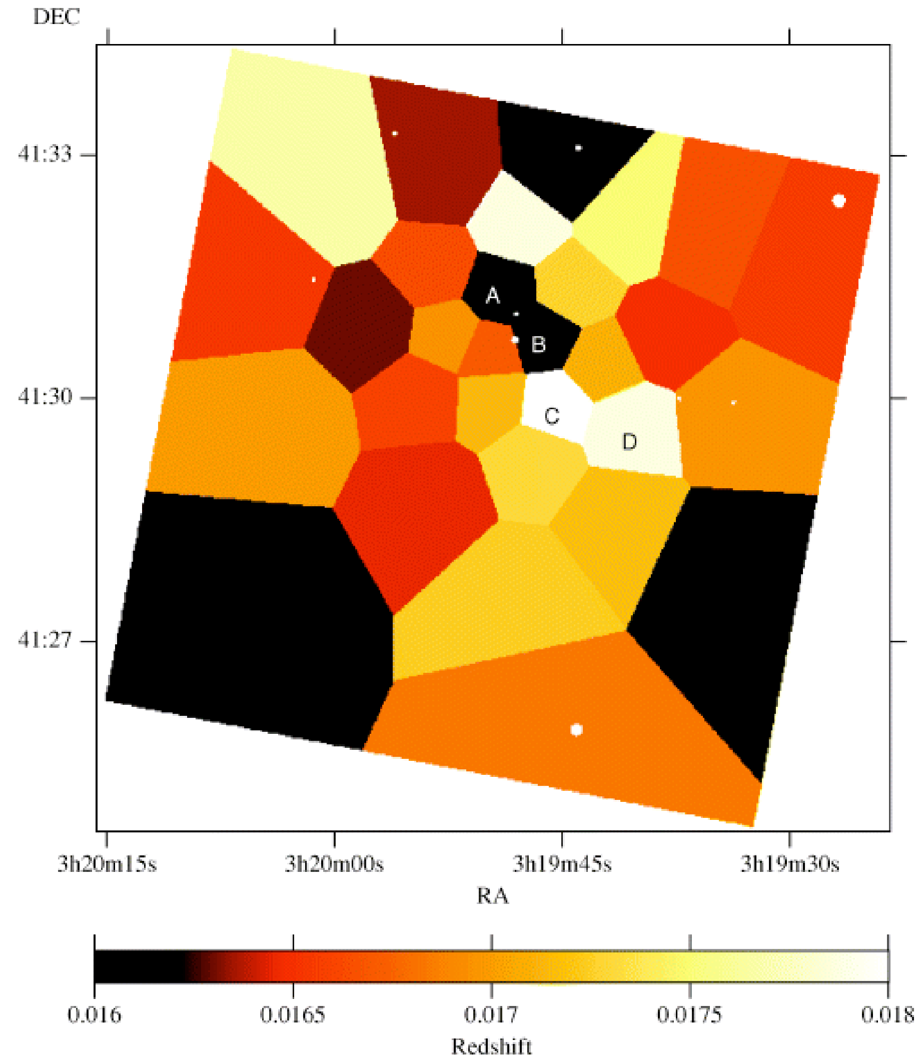
∀ τ Can be reduced by velocity structure (turbulence/shear).

- .



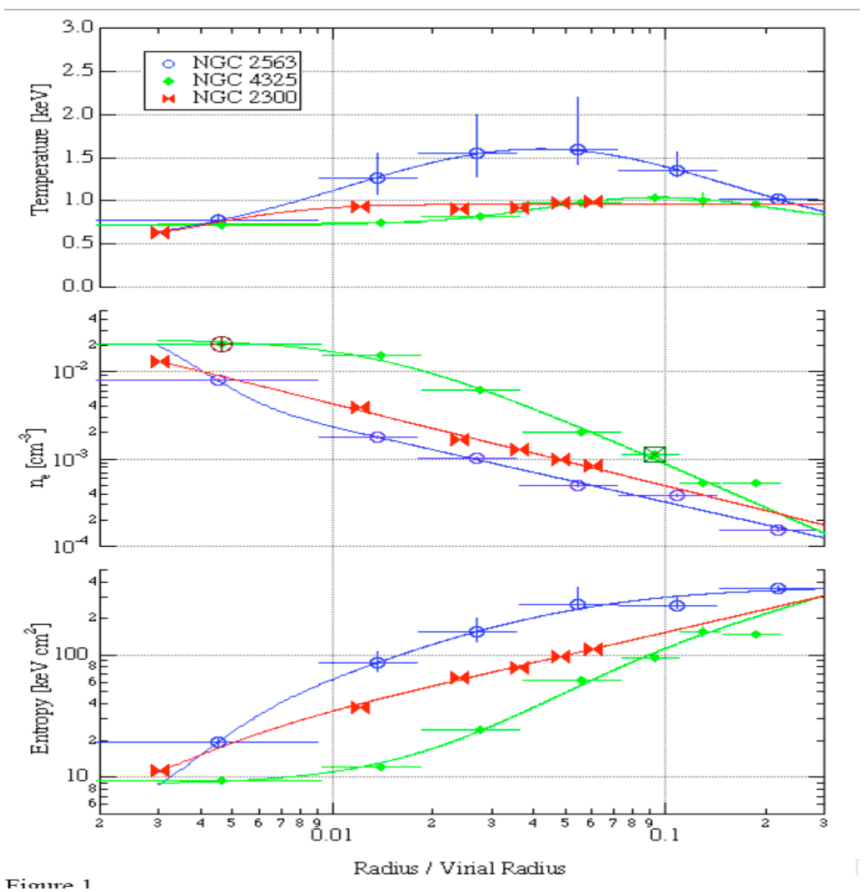
Velocity Structure

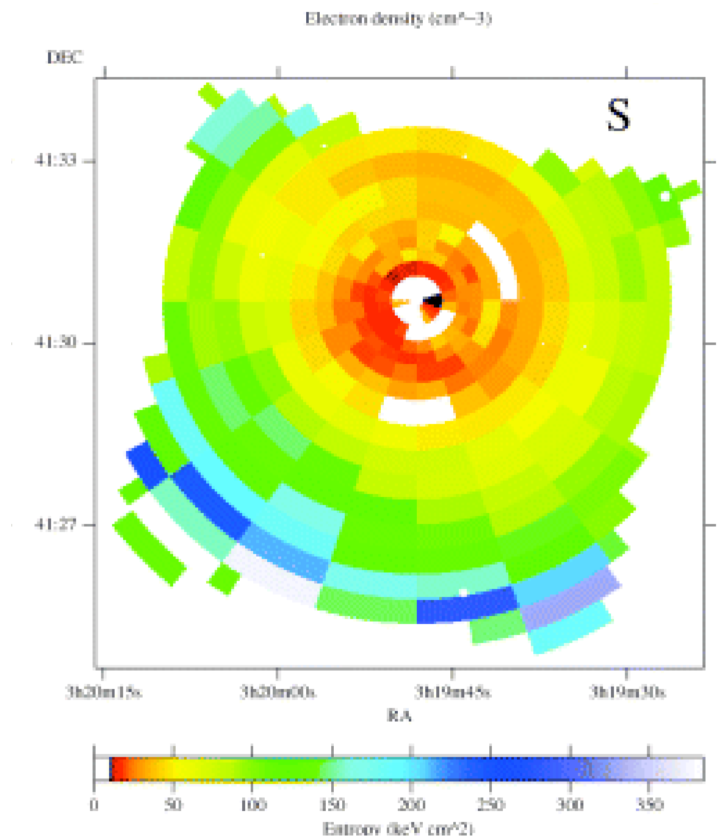
- Chandra Images of Perseus show apparent velocity structure of 600km/sec (regions A and B vs. C and D) However best fit redshift disagrees with optical
- M87 and the Perseus cluster have evidence for velocity structure with v>1/3 C (sound speed). - NGC4636 shows no velocity structure
- Astro_E2 will make a major step here- if v/c>1/4 is common it will be measured. Need better spatial resolution to study how velocity structure is related to mergers, radio sources etc.



Entropy

- The entropy of low mass systems exceeds that predicted by numerical simulations
- Origin of this “extra” heat is not clear (due to cooling, AGN, star formation etc) but dominates formation of groups/galaxies





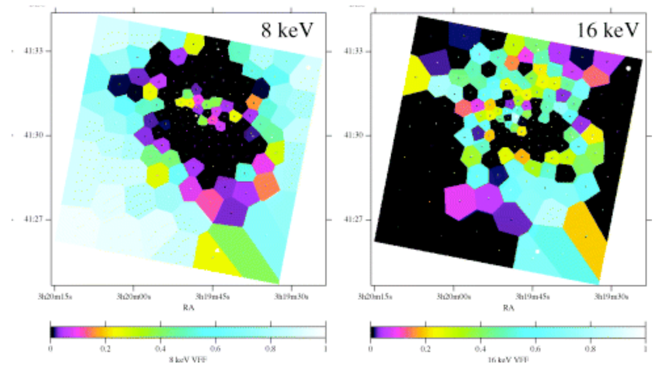
Con-X will study the entropy distribution in groups to z~0.3 and the overall entropy to z~1

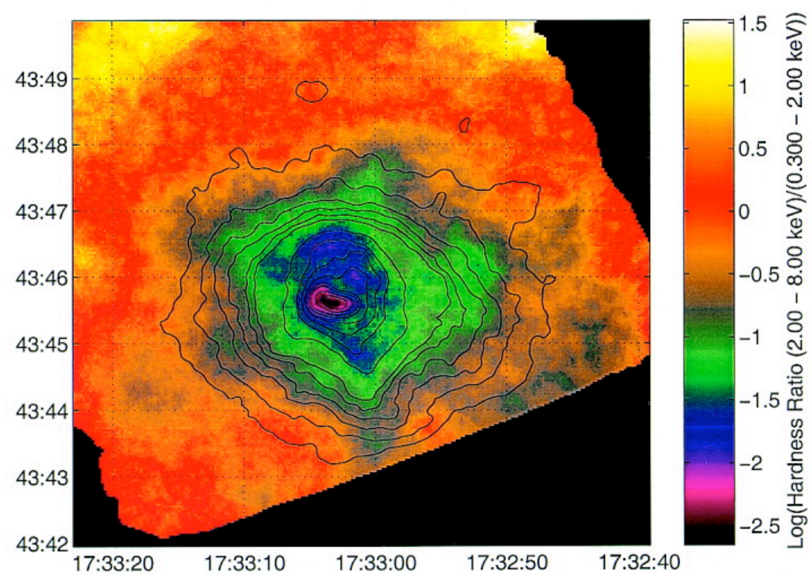
Hard X-ray Emission

- Creation of the highest energy cosmic rays is a major mystery- cluster merger shocks are one of the best locations for this - signature of energetic particles
- Chandra data have clearly shown that many clusters host x-ray bright AGN

They may dominate the hard x-ray emission

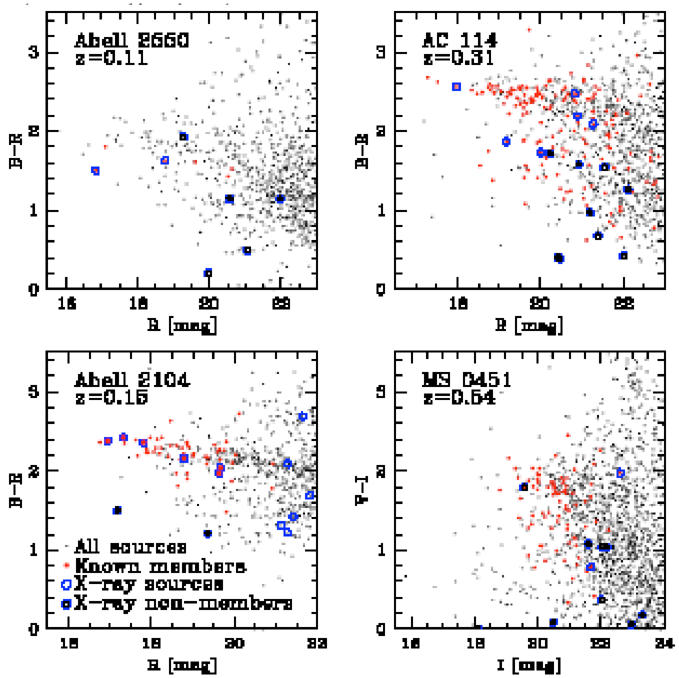
- There is evidence from SAX and XTE for hard x-ray tails which seem to be too bright to be the sum of unresolved AGN (e.g. in Coma)
- There is so far just 2 Chandra/XMM detection (IC1262 Hudson et al and Perseus cluster Saunders et al) the diffuse nonthermal emission is produced by primary electrons, accelerated at shocks to relativistic velocities



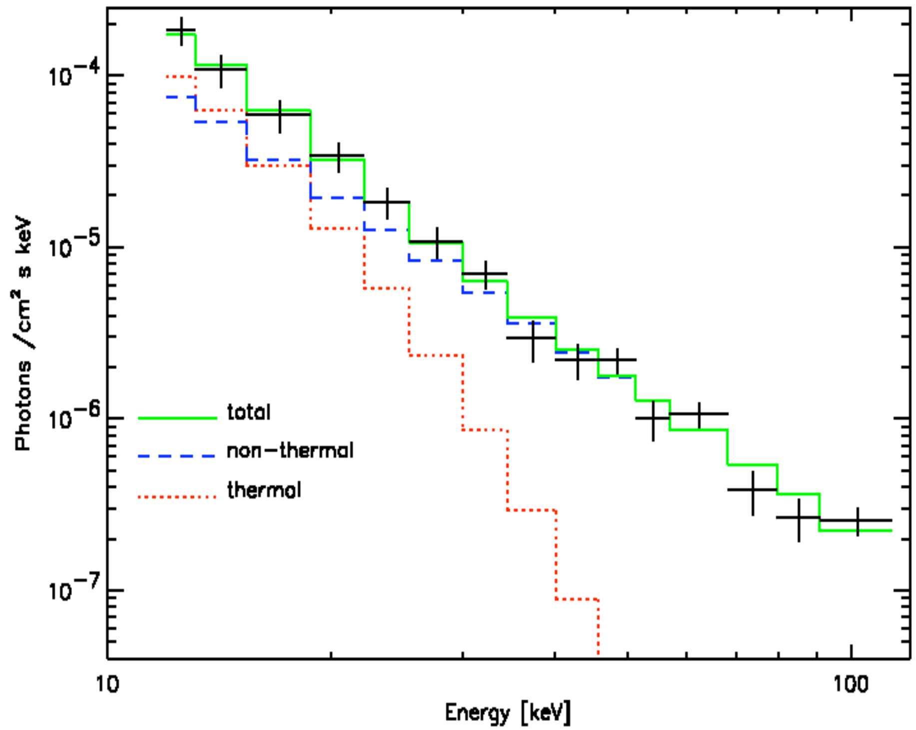


Cluster hard emission

- Composite SAX spectrum of ~15 clusters requires hard component only in merger candidates (Nevalienen e al 2003)
- Best fit hard spectrum is steep Γ=2.8+/-0.3 (560ks of SAX exposure)
- Preliminary indications is that non-thermal is extended
- XMM hard x-ray images of a few clusters (preliminary) show emission in the center- surface b



1.2. $(B-R)-R$ Color–Magnitude diagrams for the four clusters we observed in
l 2550, Abell 2104, AC 114, and MS 0451. Each panel shows all of the photon
for the cluster field (*points*) along with X-ray sources (*blue circles*), confirmed c
bers (*red dots*), and confirmed X-ray nonmembers (*stars*).

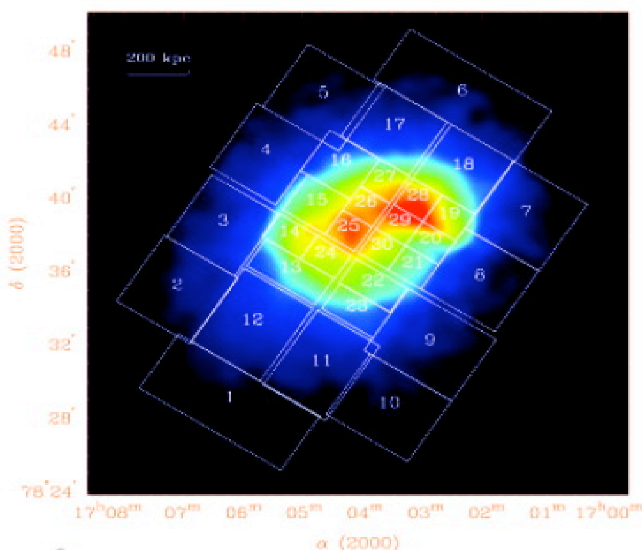


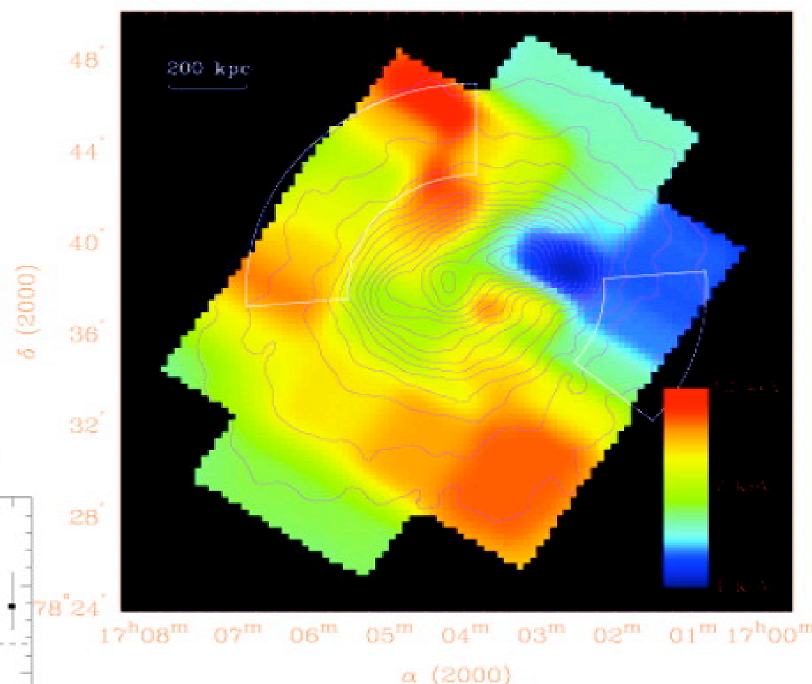
IG. 5.— The combined spectrum of all the clusters not significantly affected by AGN. The lines show the unfolded
mponents while the crosses show the data and 1 σ errors (including 20% systematics). The solid line shows the
odel. The dotted line shows the thermal contribution. The dashed line shows the best fit power-law of $\alpha_{ph} = 2.8$

Mergers, Structure etc

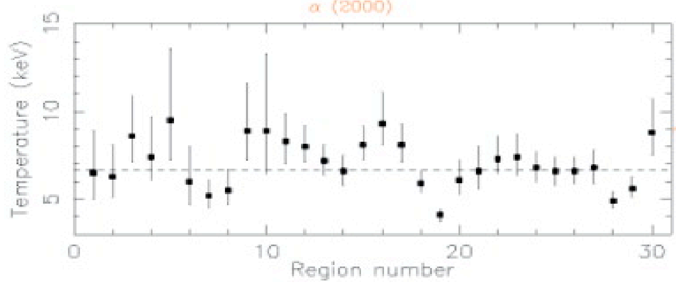
- The Classical picture has clusters forming by hierarchical mergers, Einstein and Rosat x-ray images showed many “complex” objects with double or multiple structure interpreted as mergers
- XMM and Chandra spectral imaging allow temperatures, abundances and redshift estimates of these structures.

Chandra x-ray image and temperature map for A2256 (Sun et al 2002)





Values of kT



Mergers

Expect dynamical motion, turbulence
Relative velocities
Strong shocks seem to be absent
relationship with radio emission is complex
Astro-E2 is spending ~1/3 of its cluster
time on this subject.

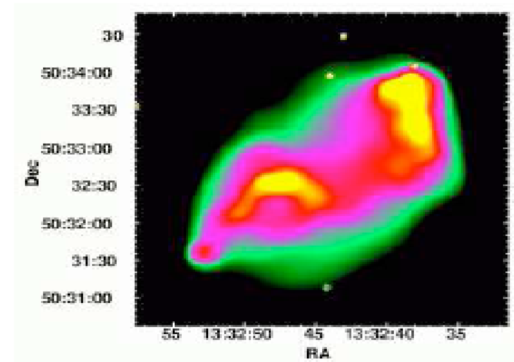


FIG. 5.— Adaptively smoothed, background-subtracted, and exposure-corrected ACIS-S3 image of A1758N.

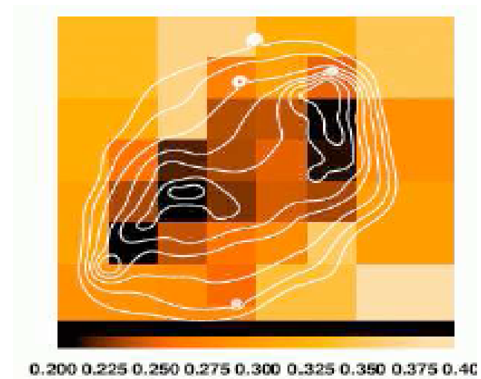
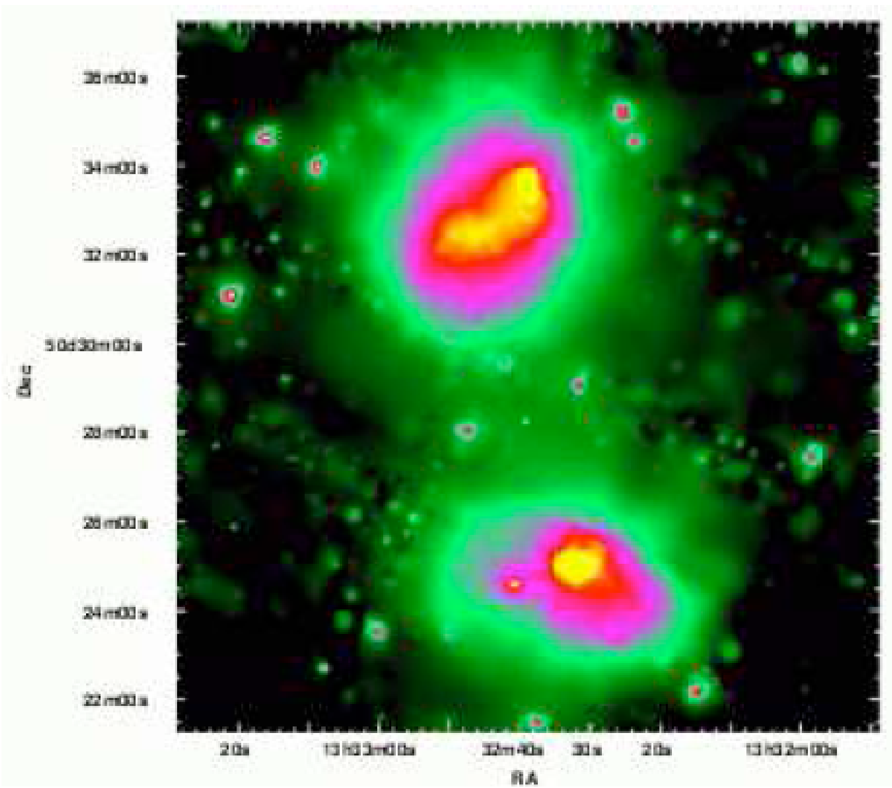


FIG. 6.— X-ray contours of the adaptively smoothed ACIS-S3 image of A1758N overlayed on an adaptively binned hardness ratio map with a maximum relative error of 10% using a soft band of 0.3–2.0 keV and a hard band of 2.0–6.0 keV. The image spans 4′ on a side. The tic marks on the color bar are spaced at approximately 1σ intervals.

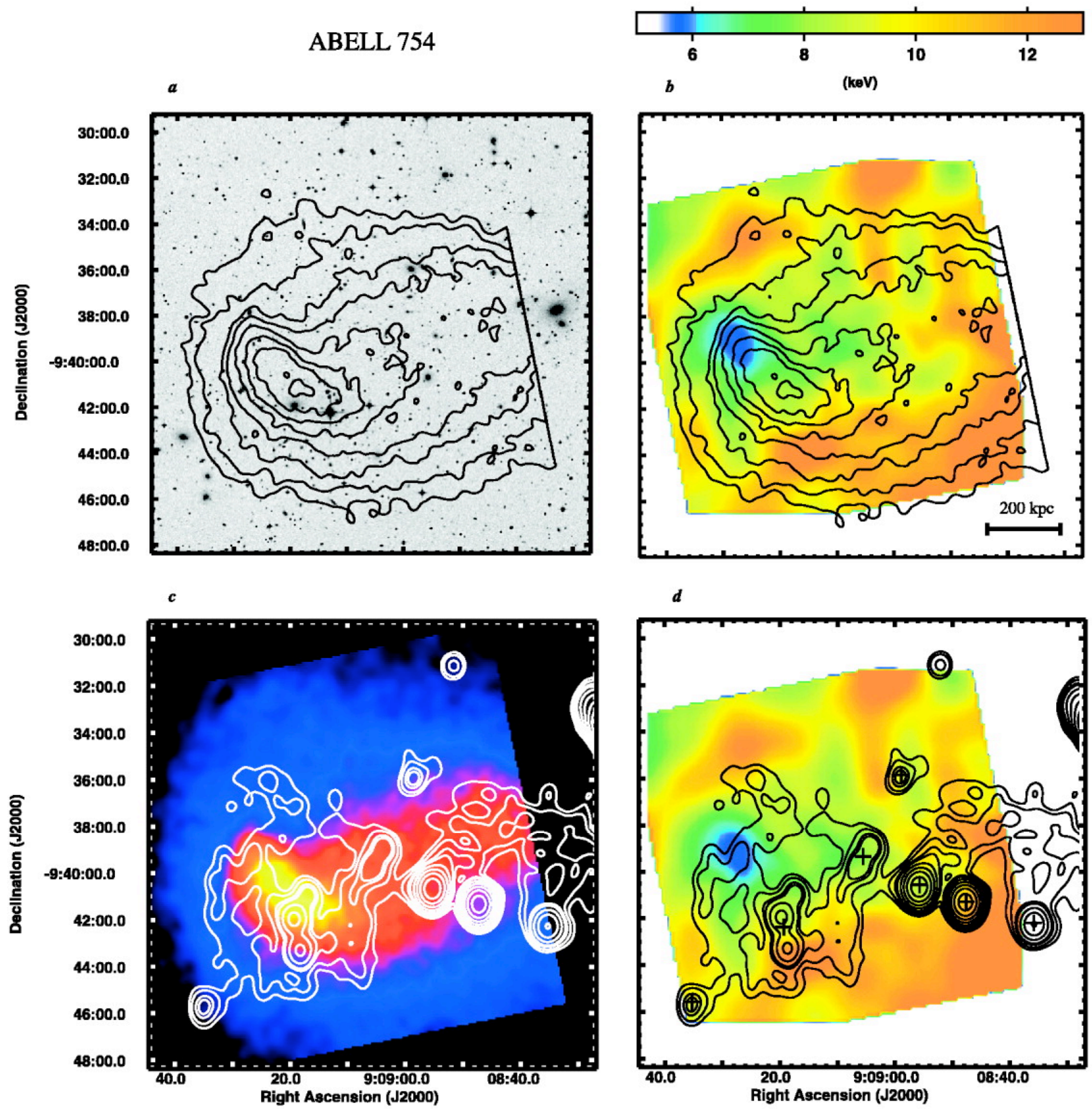


A1758- Chandra and XMM
z=0.279,1”=4.25kpc

Mergers

Chandra temperature maps of clusters are complex and not simply modeled.

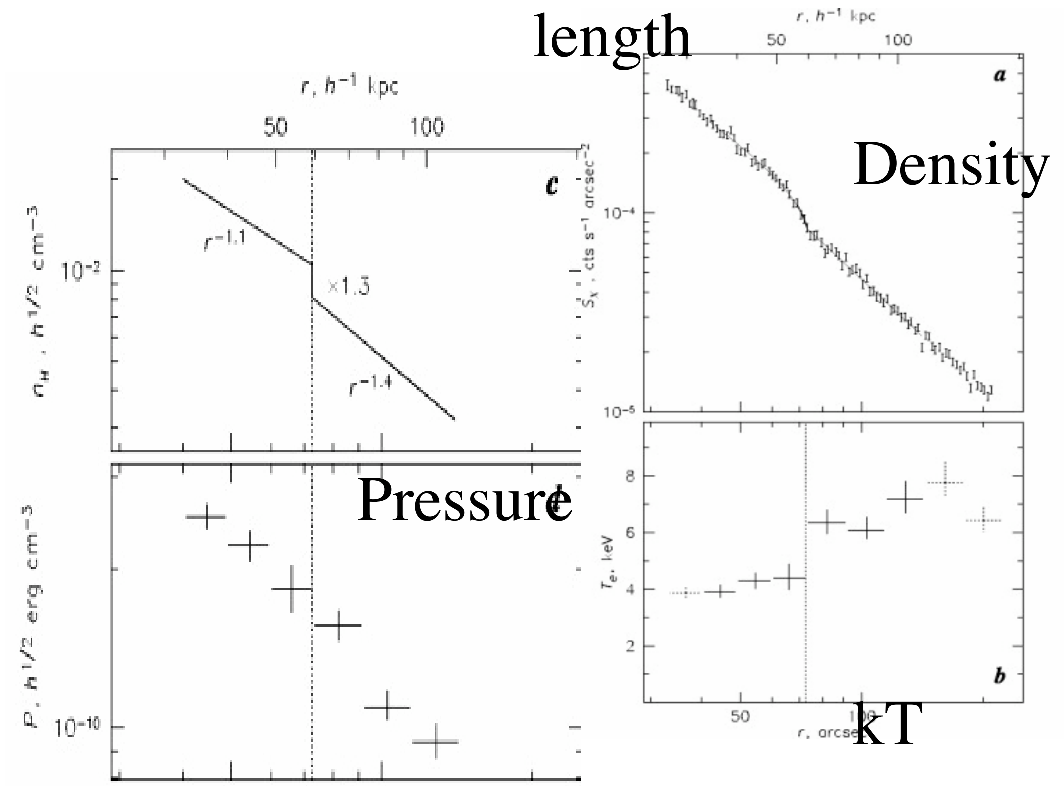
While mergers are "interesting and exciting" their detailed study is very involved, hard to think of them as science drivers for Con-X

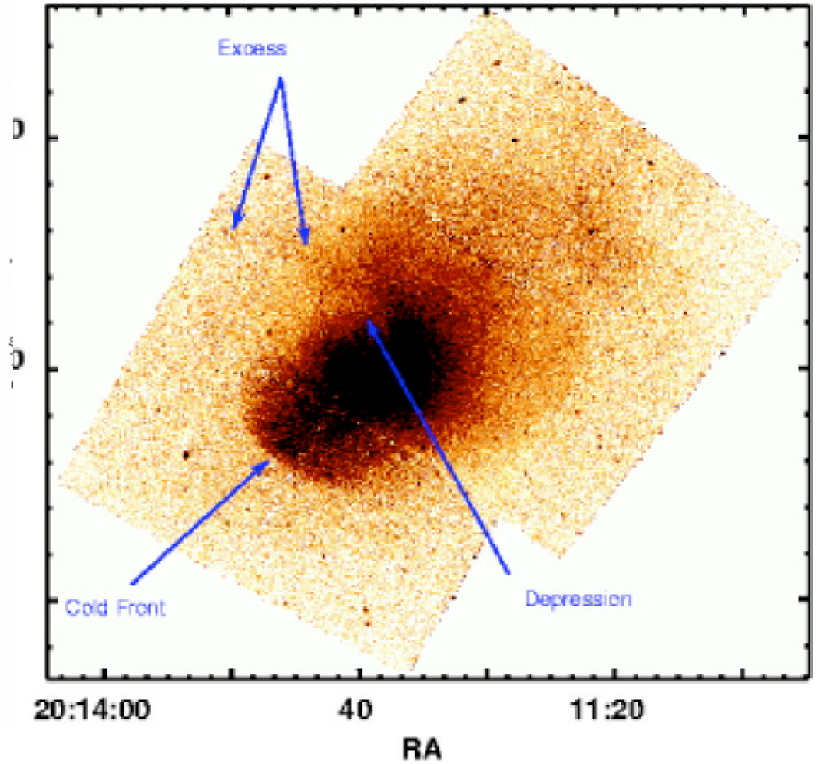


A754- Chandra and XMM
z=0.054,1"=1.04kpc

Radio on x-ray intensity and temperature

Cold Fronts- Direct Evidence for Mergers ?





Cold fronts (Vikhlinin et al 2000) are contact discontinuities across which the pressure is smooth but the density and temperature change.

They can occur in ”pure hydro” numerical simulations (Bialek et al 2002).

frequent occurrence is a indication of the merger rate.

Details (e.g. temperature drop, size of region etc) and its relation to merger dynamics are not yet certain (Fujita et al) .

For Con-X maybe an angular resolution driver -science importance not yet clear

Mergers etc

- In Abell 2256 and the Perseus Cluster there is evidence for Fe abundance variations associated with the structure.

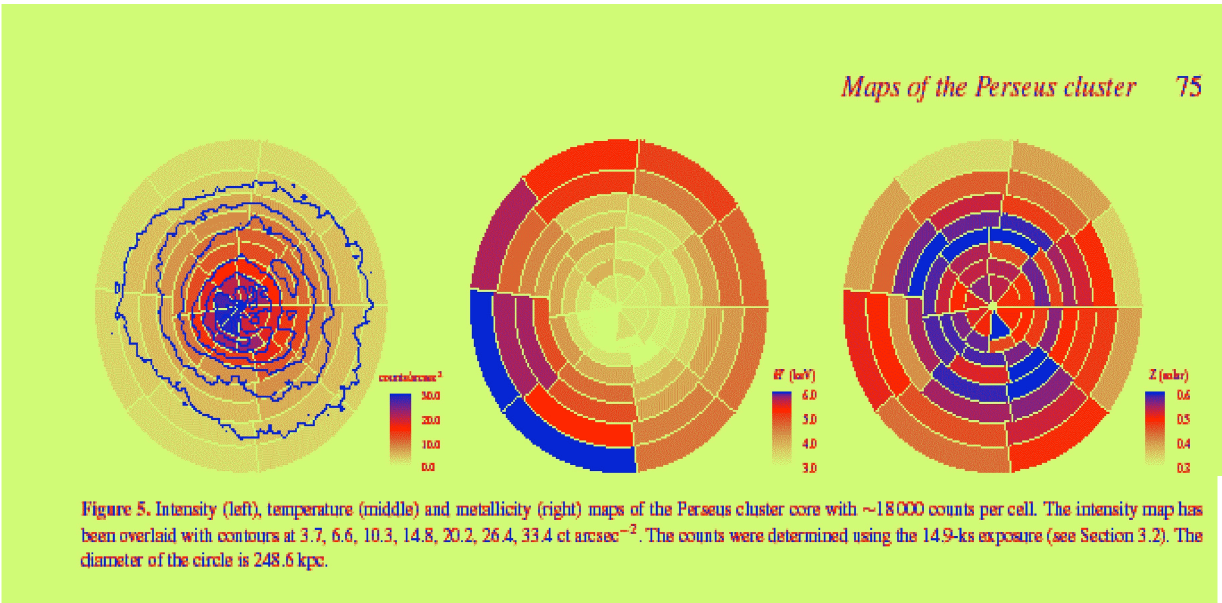
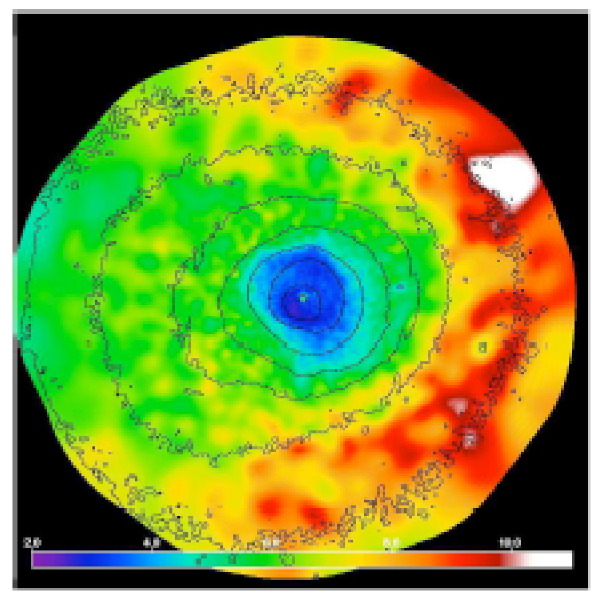


Figure 5. Intensity (left), temperature (middle) and metallicity (right) maps of the Perseus cluster core with ~18 000 counts per cell. The intensity map has been overlaid with contours at 3.7, 6.6, 10.3, 14.8, 20.2, 26.4, 33.4 ct arcsec^{-2}. The counts were determined using the 14.9-ks exposure (see Section 3.2). The diameter of the circle is 248.6 kpc.

Chandra image, kT and abundance maps of center of Perseus cluster (Schmidt et al 2002)

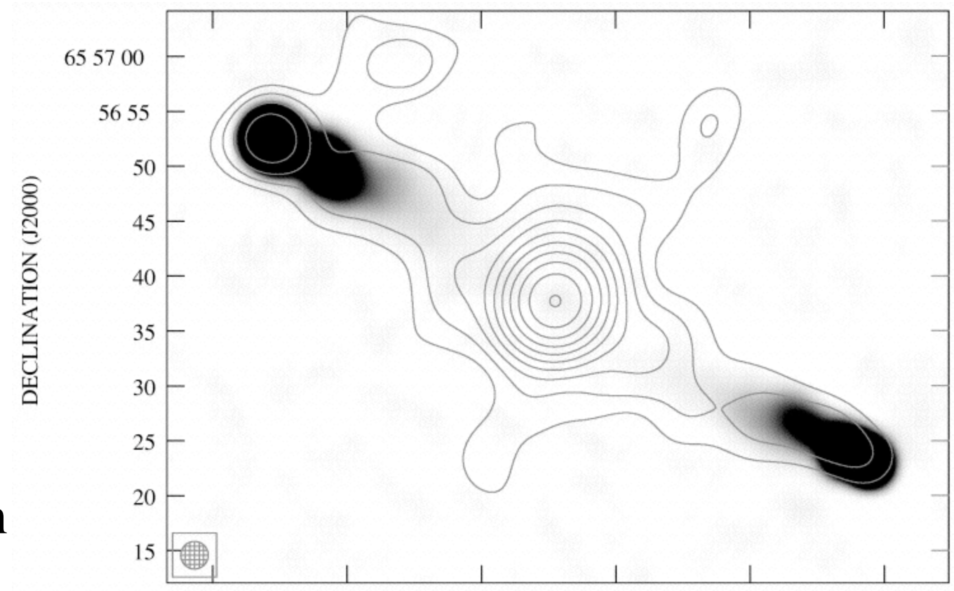
XMM Perseus temperature map Churazov et al;



More Con-X Cluster Science

- X-ray absorption of quasars along the line of sight (distance to clusters)
- Physics of magnetic fields, particles
  Inverse Compton emission from radio sources in clusters- detected from quite a few sources now (need hard x-ray imaging)
  - Angular scales so far sampled with Chandra - source separations are ~40”, source sizes <5”
  - At high redshift clusters “shine” in IC radiation $(1+z)^2$ enhancement

- Con-X can measure the spectrum of the IC emission (hard x-rays), the turbulence in the interaction region.



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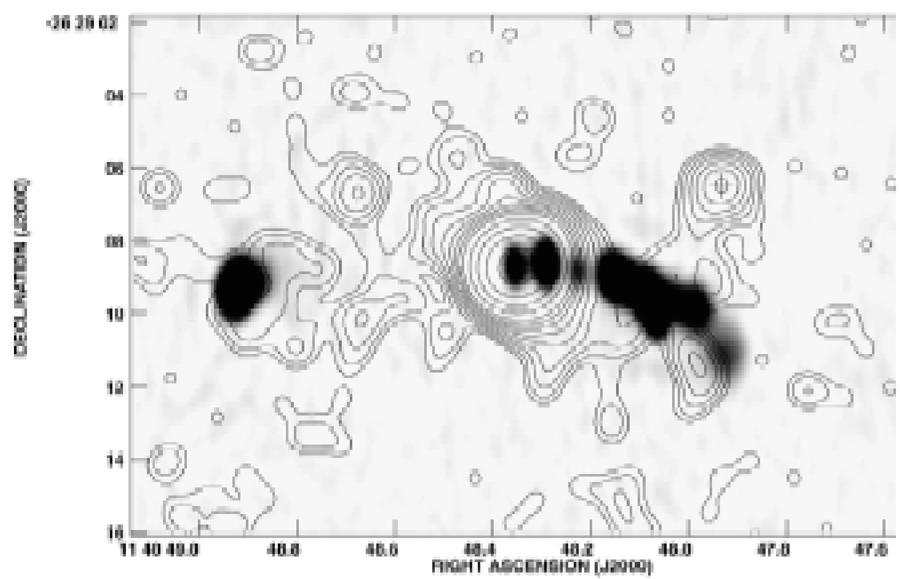
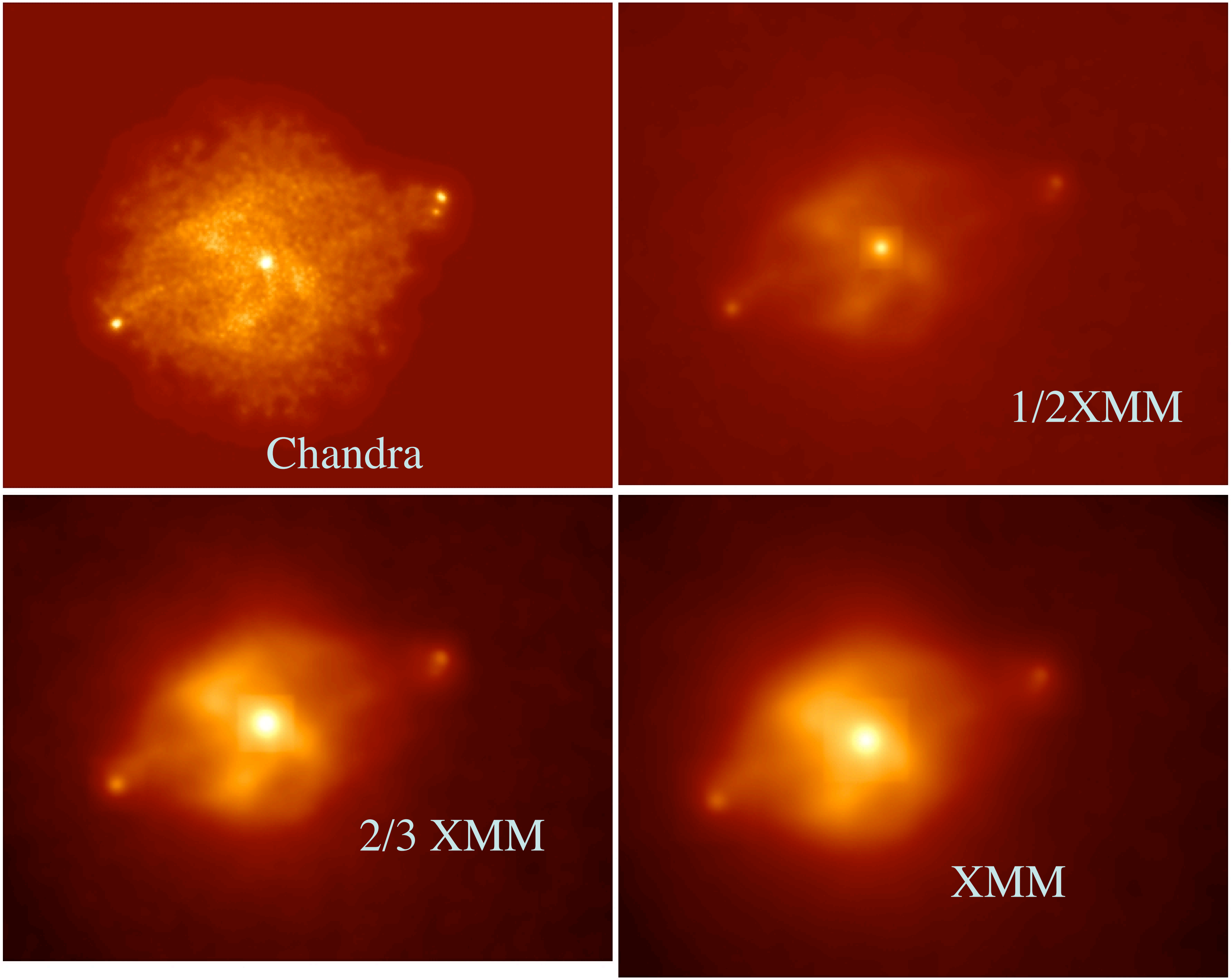
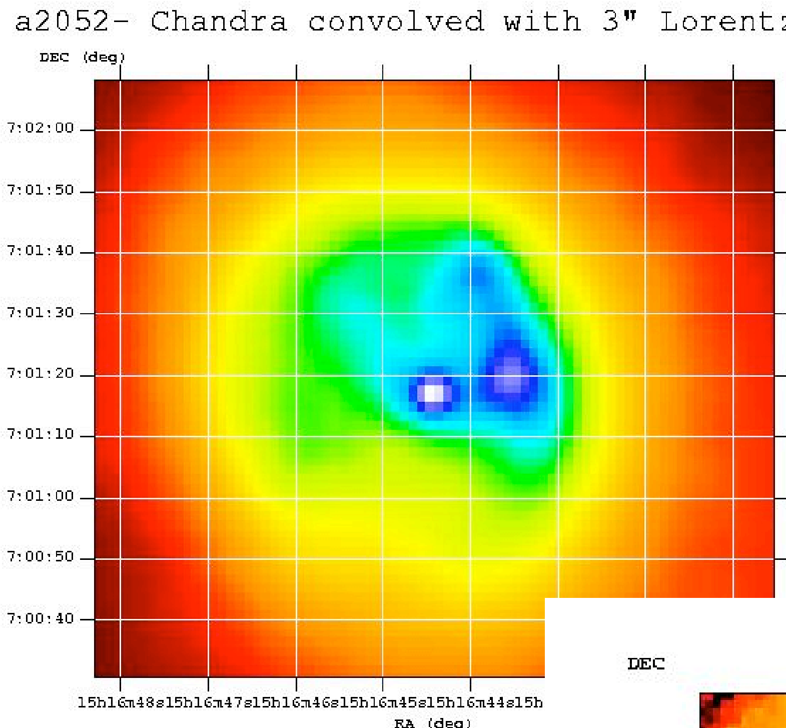
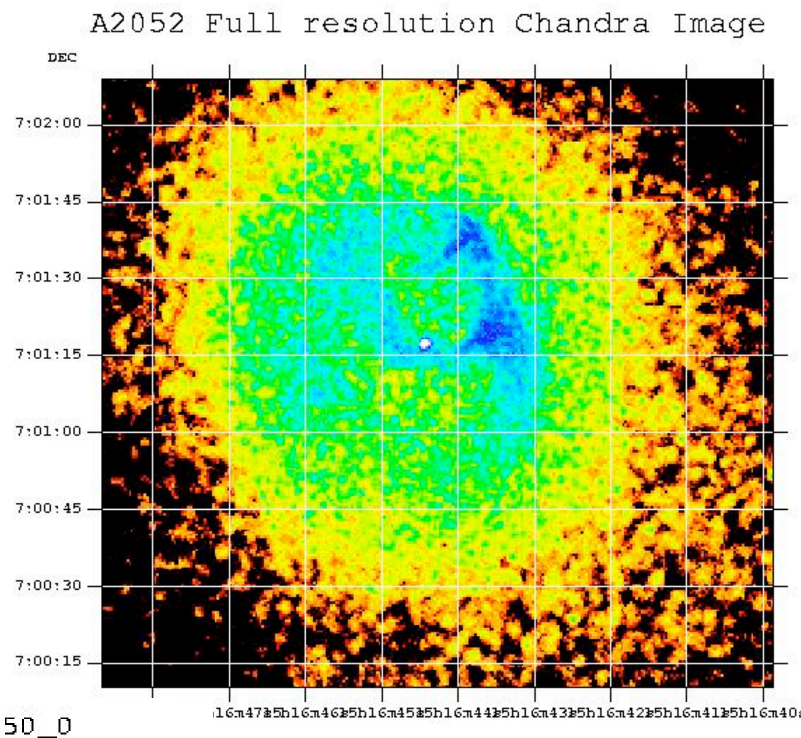


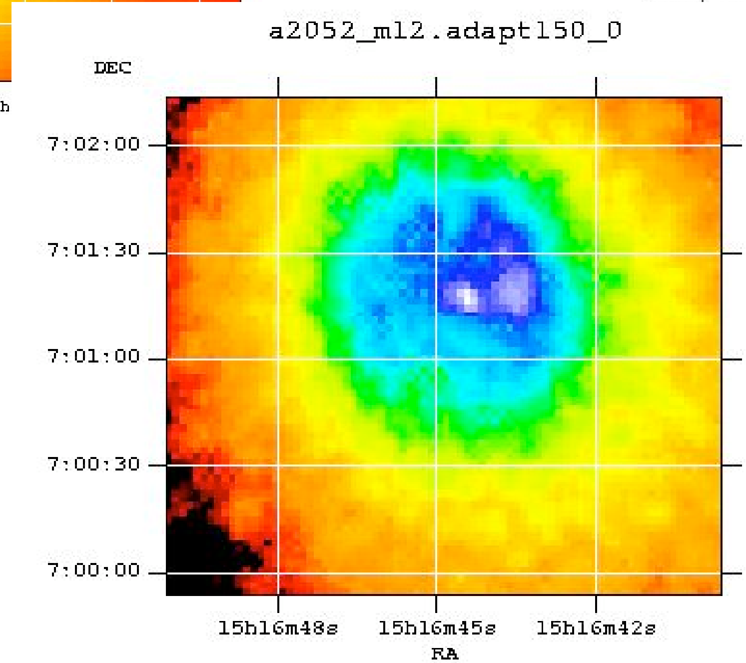
Cygnus-A Cluster



Angular resolution is[sues for A2052]







XMM

Con-X Science Drivers

SPECTRAL

- For turbulence and spectral diagnostics **Con-X has the required energy resolution**
- To observe resonance absorption against background QSO spectral resolution also adequate
- **Low background** is needed to do hard x-ray imaging, high z clusters, clusters far from center

COLLECTING AREA (1 Chandra cts/sec=0.4 Astro_E2= 25 Con-X calorimeter)

Use Astro-E simulations to calculate needed are- A~250cm2 and ~1.5' beam (HPD) exposures are ~50ks for mergers/turbulence

~100ks for cooling flows temperature structure.

If scale by ratio of area 25:1 then for constant surface brightness solid angles as small as 15" HPD are ok

Only cooling flows have sufficient brightness to go to smaller solid angles- 5" ok.

SPATIAL

It all depends on redshift range and "importance"

Cooling flows would benefit from better dθ

(absence of cooling flows at z>0.5 lessens requirements)

AGN in clusters benefit greatly from better resolution as would background AGN

Temperature and abundance structure

cold fronts

abundance patches??

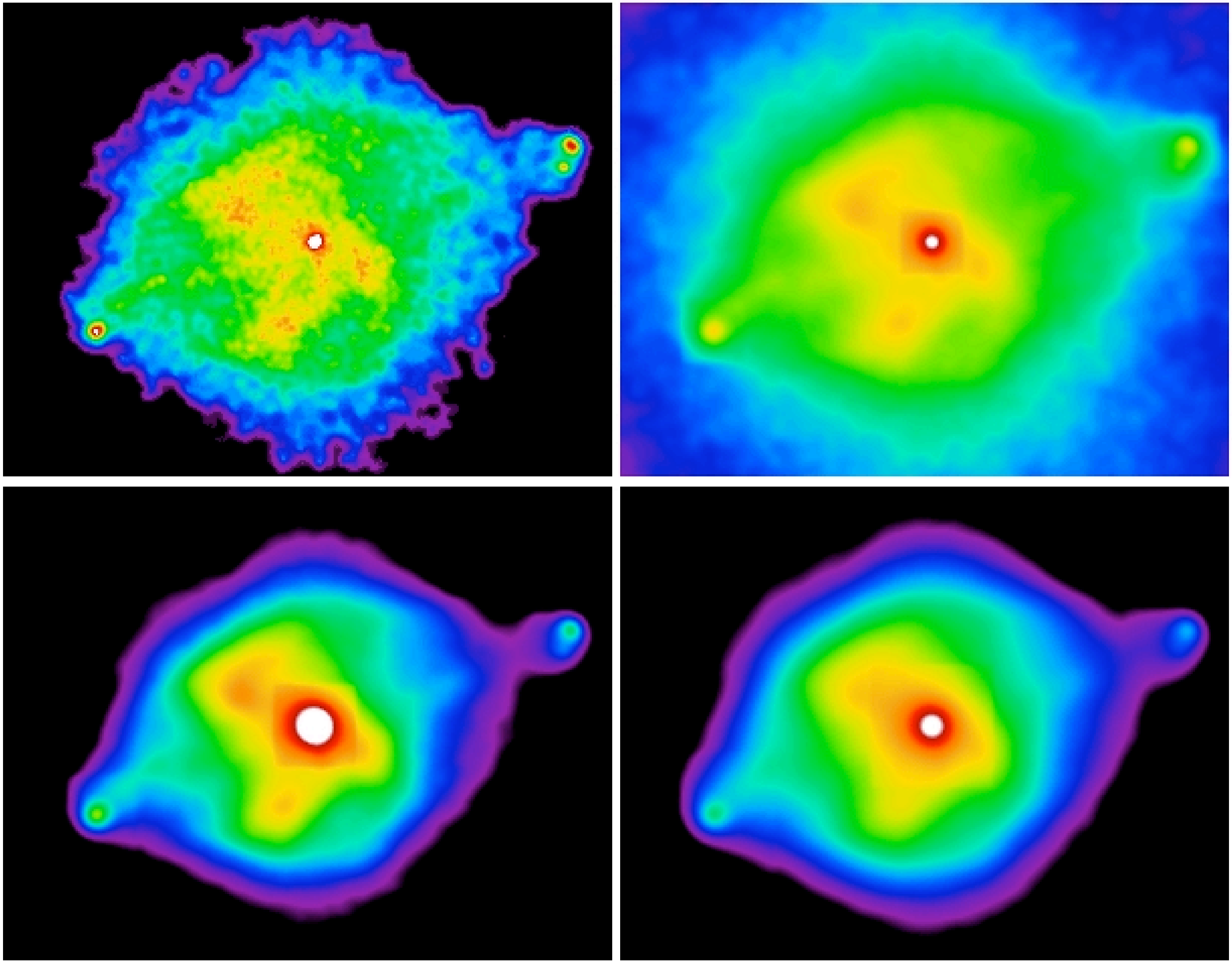
High z clusters 15" ok

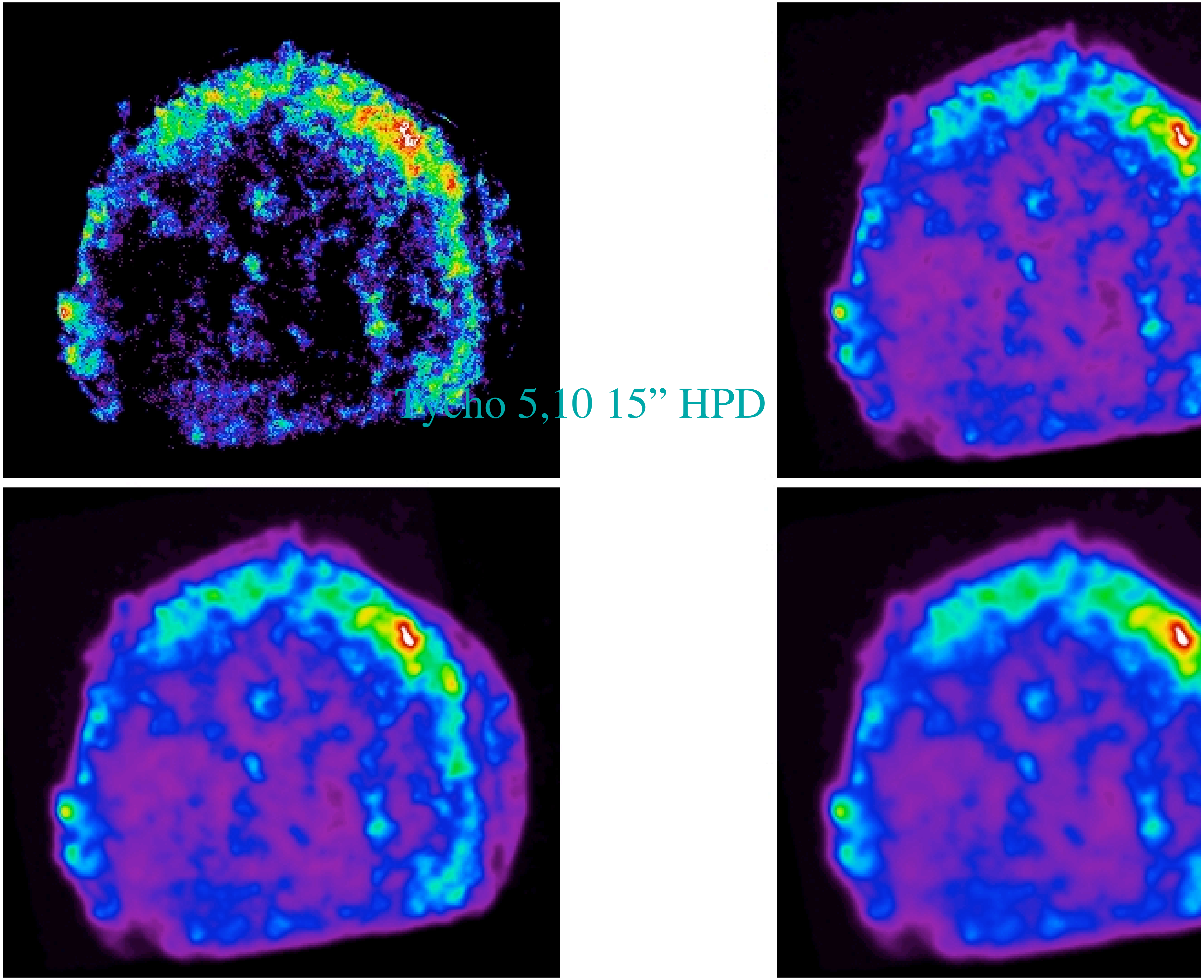
Groups 15" ok to z~0.5

Dark matter cores need dθ<10"

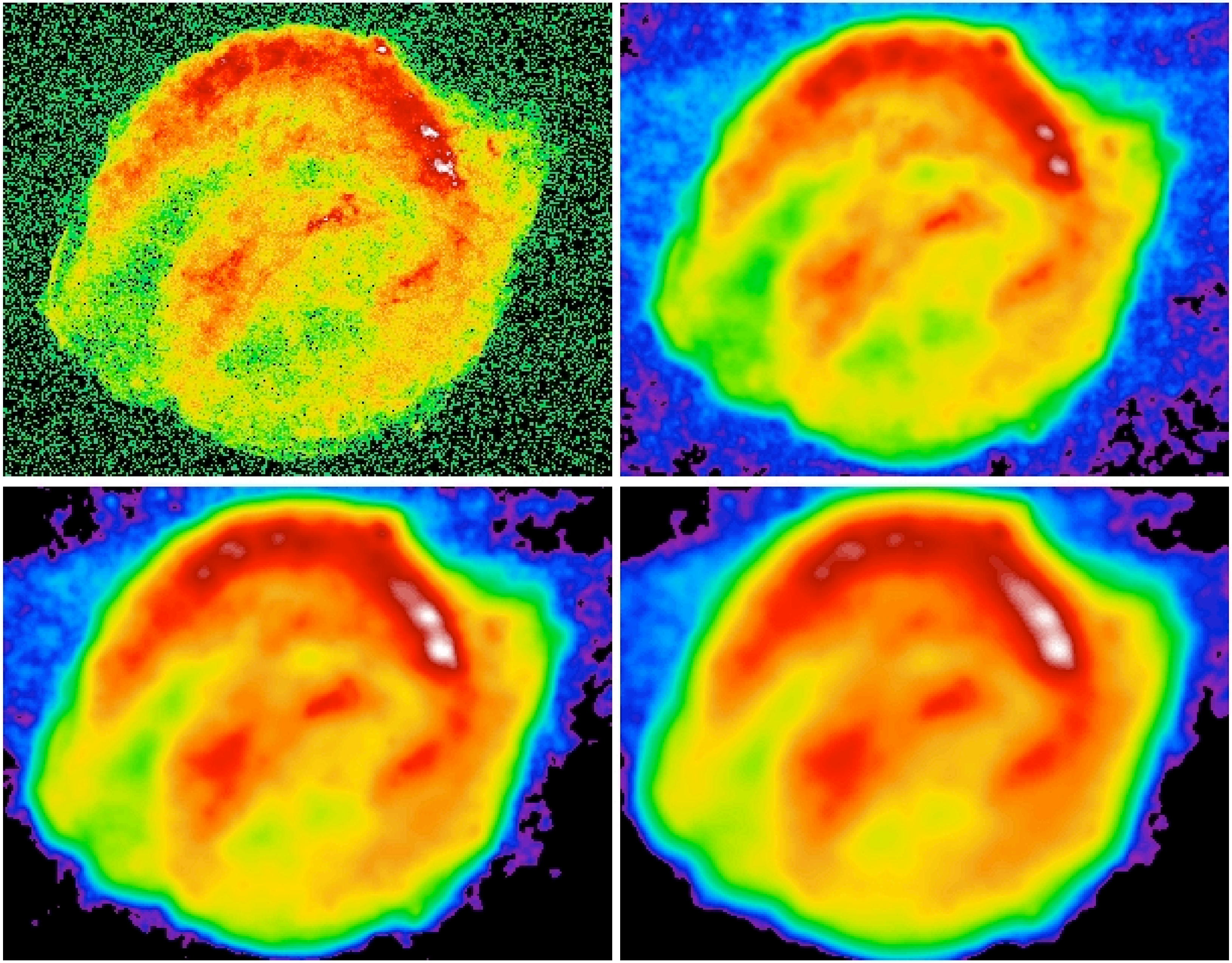
Cluster mergers- θ~15" ok at low z

Cygnus-A 5,10 15'' HPD

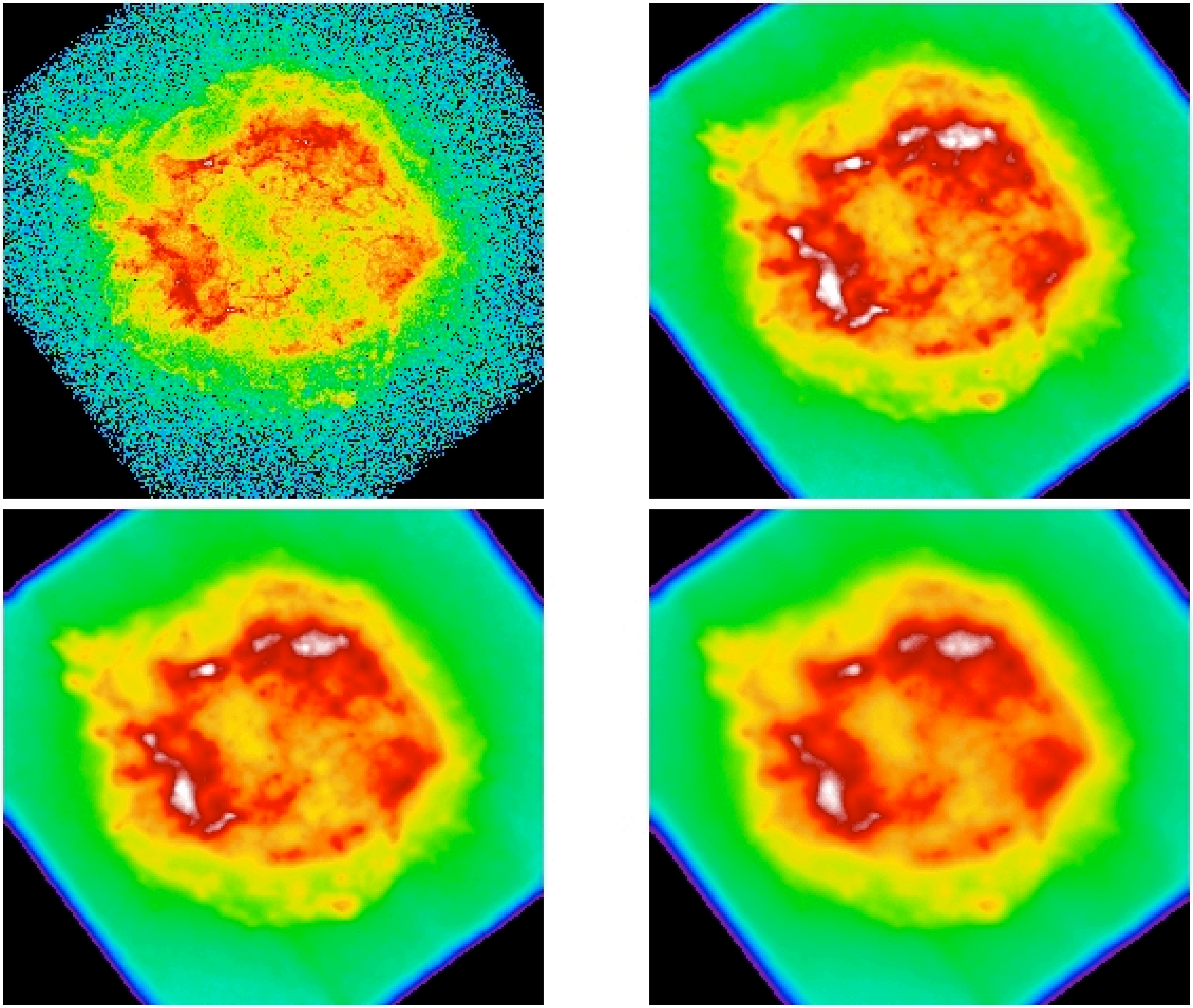



Tycho 5,10 15” HPD

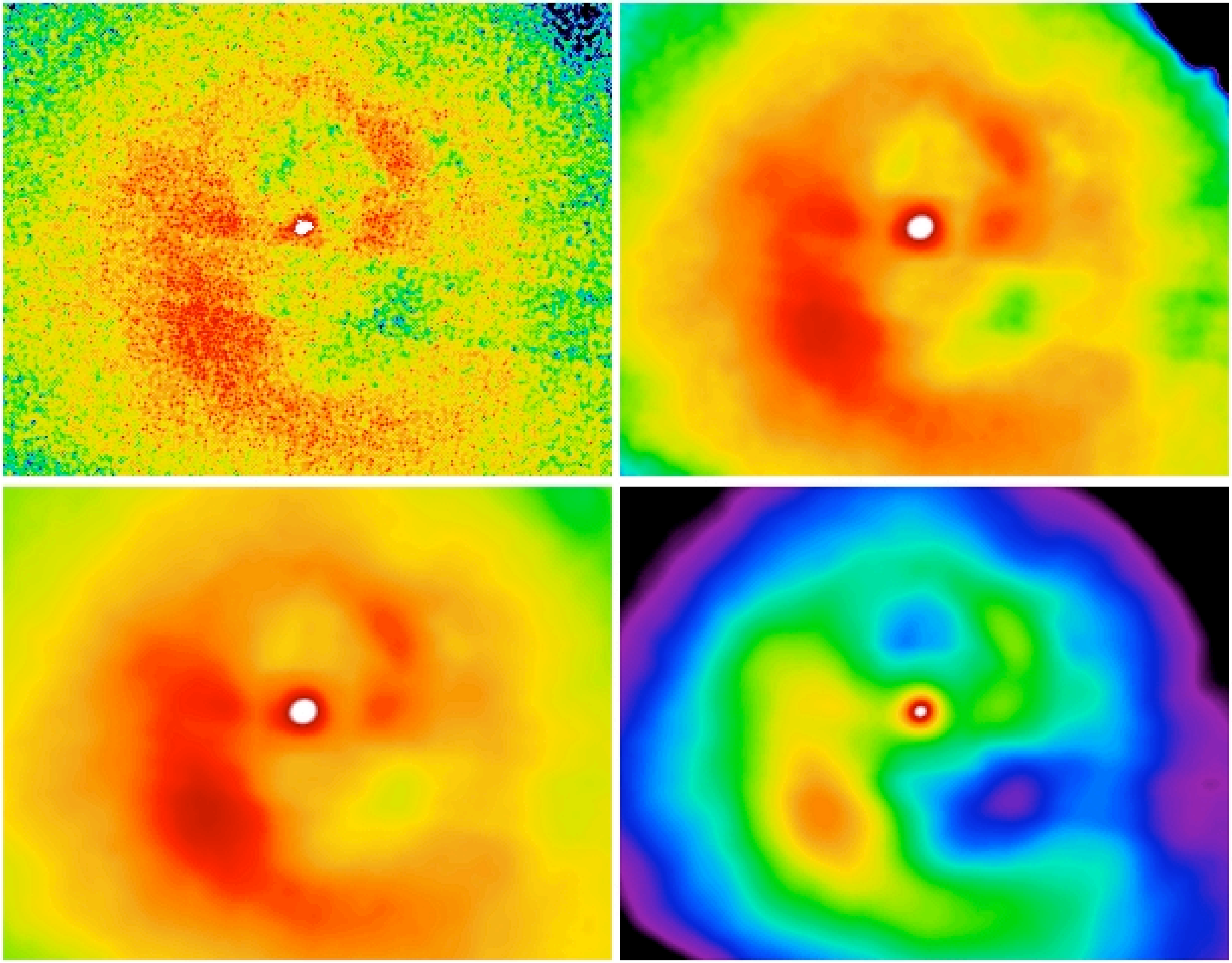
Kepler Chandra, 5,10 15” HPD



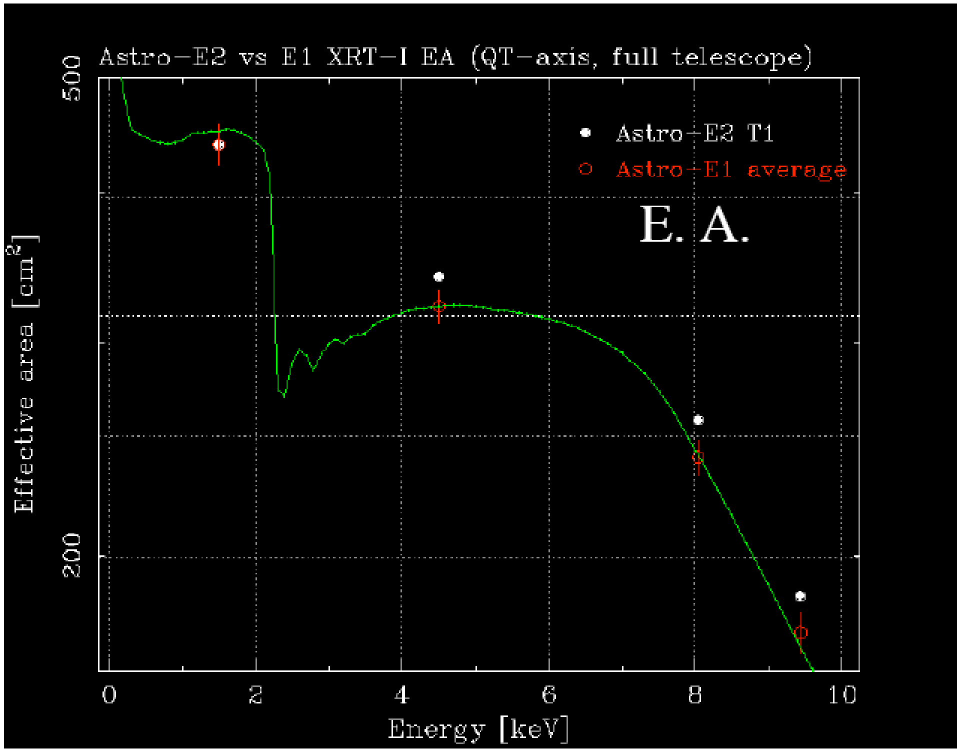
Cas-A Chandra 5,10 15" HPD



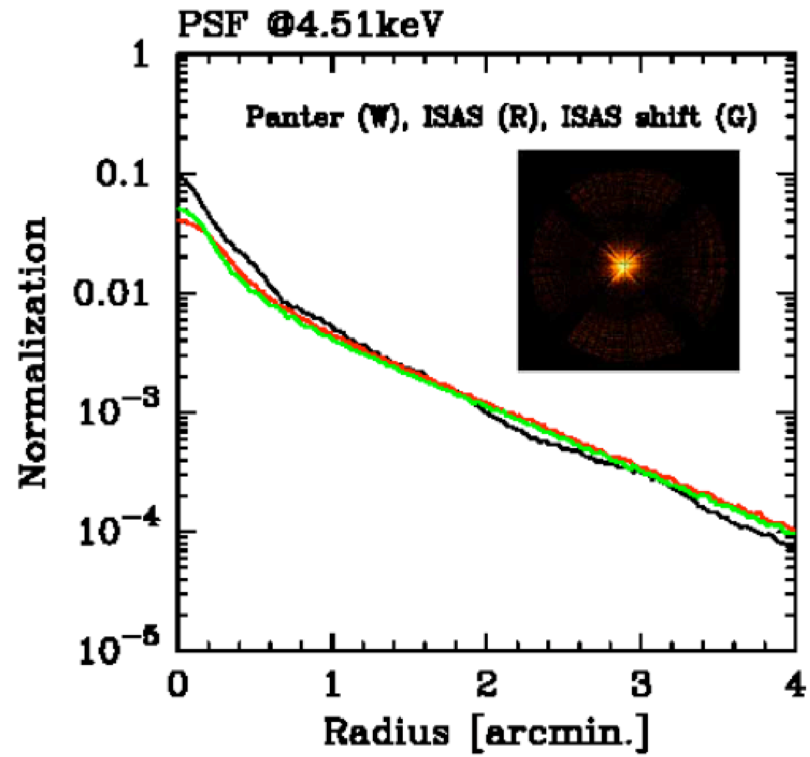
Perseus Cluster Chandra 5,10 15" HPD



Astro-E2



Astro−E2 vs E1 XRT−I EA (QT−axis, full telescope)
Astro−E2 T1
Astro−E1 average
E. A.
Effective area [cm^2]
500
200
0
2
4
6
8
10
Energy [keV]



PSF @4.51keV
Panter (W), ISAS (R), ISAS shift (G)
Normalization
1
0.1
0.01
10^−3
10^−4
10^−5
0
1
2
3
4
Radius [arcmin.]